Coffee crop coefficient for precision irrigation based on leaf area index

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Abstract

Crop coefficient (*Kc*) for coffee plantations was found to be linearly related to the leaf area index (*L*) up to 3, i.e., $Kc = b\ L$. The basic assumption is that for irrigated trees the water use per unit leaf area (ET_{LA}) is equal to the reference evapotranspiration (*ETo*) expressed also on a unit leaf area basis of the reference surface ($ET_{LA} = ETo/Lo$). As recommended by FAO-56 the leaf area index (*Lo*) for the hypothetical reference surface (grass) is equal to 2.88, then the most likely value is $b = Lo^{-1} = 2.88^{-1} = 0.347$. However, for $L > 3$ (completely covered ground surface) *Kc* decreased from a peak value (~1.05) tending to an asymptotic low value around 0.7 for $L > 6$, but the linear model gives unrealistic *Kc* estimates; tentatively the empirical function $Kc = 1.8\ L^{-0.5}$ is offered here as an initial guess due to the lack of experimental results for the interval $3.5 < L < 5.5$. To become operational under commercial fields it is necessary to estimate the leaf area per coffee tree (*LA*, $m^2\ tree^{-1}$), and based on a very limited set of data, *LA* was estimated as a function of planting density (*PD*, $trees\ ha^{-1}$), i.e., $LA = 88.38 - 8.63\ \mathrm{Ln}\ (PD)$. Alternatively, L (< 3.4) can be computed directly as a function of canopy volume (for $V < 1.2\ m^3$).

Key words: Coffea arábica L., reference evapotranspiration, soil water balance, planting density.

Coeficiente de cultivo de cafezais com base no índice de área foliar para irrigação de precisão

Resumo

Observou-se que o coeficiente de cultivo (*Kc*) para cafezais relacionou-se linearmente com o índice de área foliar (*L*), ou seja, $Kc = b\ L$ para $L < 3$. A premissa básica é que para árvores irrigadas, o consumo hídrico por unidade de área foliar (ET_{LA}) é igual à evapotranspiração de referência (*ETo*) expressa também por unidade de área foliar da superfície de referência ($ET_{LA} = ETo/Lo$). Como $Lo = 2{,}88$ é o valor recomendado pelo boletim FAO-56 para o índice de área foliar da hipotética superfície de referência (gramado), então o valor mais provável é $b = Lo^{-1} = 2{,}88^{-1} = 0{,}347$. No entanto, para $L > 3$ (cobertura total do terreno) observa-se que *Kc* diminuiu progressivamente do valor de pico (~1,05) tendendo assintoticamente a um valor mínimo ao redor de 0,7 com $L > 6$, mas o modelo linear superestima *Kc* grosseiramente; uma função empírica ($Kc = 1{,}8\ L^{-0{,}5}$) é apresentada apenas como tentativa inicial, visto que não há resultados experimentais para $3{,}5 < L < 5{,}5$. Para ser operacional em condições comerciais é necessário estimar a área foliar por cafeeiro (*LA*, $m^2\ planta^{-1}$), e com base em um conjunto bem limitado de observações foi estimada em função da densidade de plantio (*PD*, $plantas\ ha^{-1}$), i.e., $LA = 88{,}38 - 8{,}63\ \mathrm{Ln}\ (PD)$. Como alternativa, L (< 3,4) pode ser calculado diretamente como uma função do volume da copa ($V < 1{,}2\ m^3$).

Palavras-chave: Coffea arábica L., evapotranspiração de referência, balanço hídrico do solo, densidade de plantio.

1. INTRODUCTION

A world-wide shortage of fresh water is pushing the expanding agricultural production systems to improve and minimize the water use in irrigations. Nowadays irrigation is considered as the largest single consumer of water for human purpose. Consequently, to become environmentally sustainable an irrigated agronomic system needs to improve its management of water. Precision irrigations depend heavily on reliable estimates of water use by the plants on real-time. Crop evapotranspiration (*ETc*) estimates are commonly computed through the adjustment of a reference evapotranspiration (*ETo*) by an empirical crop coefficient (*Kc*), that is, $ETc = Kc\ ETo$. Under the same weather conditions of the crop *ETo* can be estimated by many methods (Doorenbos and Pruitt, 1977; Allen et al., 1998) and the one most suitable for a region depends on the availability of weather stations measurements.

For coffee plantations it is a common practice to assume that an average *Kc* value is appropriate for the whole field regardless of the tree canopy size. A single

Kc integrates both tree transpiration and soil evaporation. The FAO guidelines for computing crop water requirements recommends fixed values for two conditions of coffee cultivations, that is, $Kc = 0.9$ if kept free of weeds, otherwise $Kc = 1.1$ (Allen et al., 1998). However, for arabic coffee trees growing in a high altitude tropical climate of Ruiru, Kenya, monthly mean values of *Kc* varied from 0.5 (during dry season) to 0.8 (during rainfall season) with *ETo* measured by a sunken pan (Pereira, 1957). For the same location Blore (1966) found $Kc = 0.86$ taking 10-day averages during the wet season without soil water deficits.

An approach used in Zimbabwe allows *Kc* to vary with age/size/planting arrangement of trees as it is defined as the ratio of the canopy area to the planted area (Carr, 2001). Camargo and Pereira (1994) recommend that *Kc* be estimated as 1.2 times the fraction of ground shaded by coffee trees around noontime to allow for values above 1.0, the limit for completely shaded ground area, and for seasonal leaf area changes. Similarly, the water use for a grapevine orchard (Williams and Ayars, 2005) and for an isolated peach tree (Goodwin et al., 2006) was found to be linearly related to the shaded area casted on the ground beneath the canopy around noontime. For grapevines *Kc* was linearly related to the leaf area index (*L*) up to 4.5 (Williams et al., 2003; Williams and Ayars, 2005; Netzer et al., 2009). Theoretically it is more correct to use *L* then shaded area as it represents the ratio of the total canopy leaf area to the planted area (Ritchie and Burnett, 1971; Fuchs et al., 1987; Al-Kaisi et al., 1989). Even though more difficult to operate in real-time irrigations schemes this approach considers the total effective transpiring leaf area.

For a young and growing coffee crop with 4 000 plants ha^{-1} it has been found by Villa Nova et al. (2002) that *Kc* is well represented by a fixed proportion of *L* (up to 3.4), that is, $Kc = 0.347\ L$. However, the nowadays coffee cultivations tend to have high planting rates (hedgerows) and sometimes *L* approaches extremely high values (> 7.5); obviously, under such growing system such linear relationship will give unrealistic *Kc* values (= 2.6). It will be shown here that $Kc = 0.347\ L$ is theoretically sound as the 0.347 coefficient can be deduced from the assumption that water use per unit leaf area is similar for different species under the same atmospheric demand (*ETo*).

However, such linear model must have an upper limit of application and results from Gutiérrez and Meinzer (1994a) are used to infer that the limit is around $L = 3$. Micrometeorological changes due to the canopy growth are discussed to support such inference. As recommended elsewhere (Pereira et al., 2006; Fernández et al., 2008) in order to become an operational tool in real-time precision irrigation schemes it is necessary an easy way to estimate plant leaf area. Simple empirical relationships between plant leaf area and planting rate or canopy volume are also presented to help the use of such approach in irrigations schemes of commercial coffee fields.

2. MATERIAL AND METHODS

The experiment was performed on a sprinkler irrigated young coffee plantation in order to detect the effect of the growing plant leaf area on the crop coefficient (*Kc*). Arabic cultivar Mundo Novo IAC 388-17 grafted on Apoatã IAC 2258 was planted on a 2.5 m by 1.0 m spacing (4000 plants ha^{-1}) on a Rhodic Kandiudalf clay texture soil. The experimental site was located in Piracicaba, São Paulo, Brazil (22° 42′ S, 48° 39′ W, 511 m asl). To avoid soil water deficit weekly irrigations replaced the accumulated reference evapotranspiration (*ETo*, mm d^{-1}) given by a Class A pan evaporation (E_A, mm d^{-1}) in a standard weather station about 200 m away ($ETo = E_A\ Kp$). For each period the pan coefficient (*Kp*) was estimated by the equation of Snyder (1992) with a fixed grass buffer area (= 10 m), and averages wind speed and relative humidity at 2 m above the grass surface of the nearby weather station.

Field measurements began 15 months after transplantation (8/1998) and lasted until the coffee plants were 40 months old (9/2000). Soil water balance was performed taking soil samples for water content down to the 0.6 m depth (including 100% of the roots) in two symmetric positions below 2 trees canopies and about 0.2 m from the tree trunk. This procedure was repeated after 3 to 5 days to compute the average water used (*ETc*) by the trees during the time interval. The time interval was determined by the weather forecast to avoid disturbing rainfalls. After the second soil sampling all leaves of the two trees were collected and the total leaf areas were digitally measured by an area meter (LI-COR model 3100). Leaf area index (*L*) at each time was calculated taking the crop spacing (2.5 m^2) as the available ground area for the tree.

For each period the average *ETc* (L $tree^{-1}$ d^{-1}) was assumed to be equal to the change in the volumetric soil water content ($m^3\ m^{-3}\ d^{-1}$) times the soil volume (m^3). Soil volume varied with crop age and it was defined by the surface area covered by the canopy times de 0.6 m depth as roots of frequently irrigated coffee trees seldom go deeper than such depth (Favarin et al., 2001). The coffee crop was kept free of weeds to ensure that the soil water depletion was due mainly to the tree transpiration. To compute the crop coefficient (*Kc*) values the *ETc* was converted to mm d^{-1} (i.e., L $tree^{-1}$ d^{-1}/m^2 of ground $tree^{-1}$ = L m^{-2} of ground d^{-1} = mm d^{-1}) considering the crop spacing.

Results from Gutiérrez and Meinzer (1994a) obtained in Hawaiian coffee fields were incorporated in the analysis in order to have *Kc* values for crops with *L* up to 7.5. Re-analysis of available literature data and results, even with other species, were incorporated and reinterpreted to substantiate the discussion and to define thresholds. Graphical and statistical comparisons were performed to substantiate the discussion of the results whenever enough data are available.

3. RESULTS AND DISCUSSION

Results obtained during the Piracicaba experiment are summarized in table 1. The water use (*ETc*) increased from 0.2 mm d^{-1} to about 4 mm d^{-1} as the coffee trees aged from 15 to 40 months-old. At the beginning the coffee trees were very small and each one had about 0.67 m^2 of leaf area (*LA*); but, at the end of the experiment they had grown up to over 7 m^2 per tree. The leaf area index (*L*) varied from 0.27 up to 3. During such period *Kc* increased continuously from 0.1 to about 1.0 associated with the increase in *LA*. Both, *Kc* and *LA* increased proportionally by a factor of 10.

As the transpiring area increases the water use has to increase proportionally in the same weather conditions if soil water is not limited. This was observed in a short-term (6-day) de-branching experiment with a peach tree (Goodwin et al., 2006). One way to eliminate the effect of the tree size on the transpiration rate is to express the water use on a unit leaf area basis (ET_{LA}), or leaf water efficiency (Hatton et al., 1998). This way it can be seen that, regardless of the coffee tree size (leaf area), ET_{LA} had similar values during periods with similar *ETo*. For instance, comparing periods when the trees had very distinctive leaf areas (e.g., at 15 and 25 mo-old) but were under similar *ETo* values (1.95 and 2.0 mm d^{-1}, respectively) they had almost identical values of ET_{LA} (i.e., 0.75 and 0.82 L m^{-2} leaf area d^{-1}). The same occurred at ages 17 and 35 mo-old when *ETo* of 3.62 and 3.53 mm d^{-1} resulted, respectively, in ET_{LA} of 1.14 and 1.09 L m^{-2} d^{-1}. Consequently, a simple linear regression analysis forced through the origin (Figure 1) shows that a linear equation describes conveniently the results, i.e., ET_{LA} = 0.31 (± 0.05) *ETo* (R^2 = 0.47; n = 9; the largest *ETo* value disturbed R^2 but not the *b* coefficient). This indicates that the water use per unit leaf area was about 1/3 of *ETo*.

It is interesting to note that the present results is substantiated by those obtained previously with different plant species such as grapefruit in Israel (Cohen, 1991), grapevine grown in California, USA (Fig 9 in Williams and Ayars, 2005) and in Israel (Fig 4 in Netzer et al., 2009), apple, olives, walnut, Asian pear, and grapevines grown in New Zealand and Spain (Pereira et al., 2006; Fernández et al., 2008), and Tahiti acid lime in Brazil (Pereira and Villa Nova, 2009). Such results with very distinctive crops show that ET_{LA} becomes independent of plant size and tend to merge in a unique linear relationship of *ETo*. Indeed there was a very narrow range of the regression coefficients (0.34 to 0.36) for each tree (Pereira et al. 2006; Pereira and Villa Nova, 2009).

Another important aspect to observe is that the empirical regression coefficients discussed above can be derived theoretically if it is assumed that the water use per unit leaf area of the irrigated trees (ET_{LA}) is equal to the reference evapotranspiration (*ETo*) also expressed per unit leaf area of the reference surface (*Lo*), i.e., ET_{LA} = *ETo*/*Lo* (Villa Nova et al., 2002; Pereira et al., 2006). The reference surface was defined by Allen et al. (1998) as a hypothetical grass field with constant *Lo* = 2.88. Consequently, the most likely value for the linear regression coefficient is 2.88^{-1} = 0.347. Therefore, *Kc* = 0.347 *L*, as proposed by Villa Nova et al. (2002), is theoretically sound for orchard

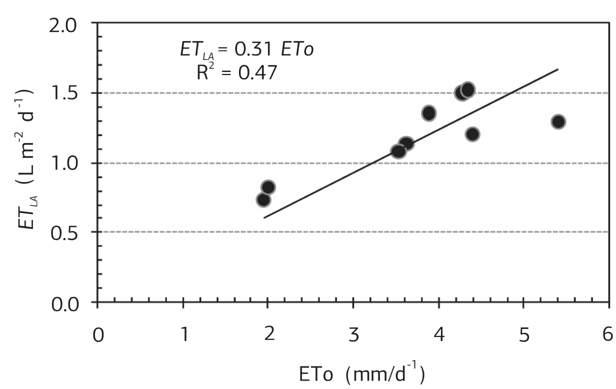

Figure 1. Linear regression between water use per unit leaf area (ET_{LA}) and reference evapotranspiration (*ETo*).

Table 1. Time variation of water use (*ETc*), reference evapotranspiration (*ETo*), crop coefficient (*Kc*), leaf area (*LA*), leaf area index (*L*), and water use per unit leaf area (ET_{LA}) of young irrigated arabic coffee trees in Piracicaba (SP) Brazil

Crop Age (months)	*ETo* (mm d^{-1})	*ETc* (mm d^{-1})	*Kc* ---	*LA* (m^2 $tree^{-1}$)	*L* ---	*ETLA* (L m^{-2} d^{-1})
15	1.95	0.20	0.10	0.67	0.27	0.75
17	3.62	0.66	0.18	1.45	0.58	1.14
20	5.40	0.87	0.16	1.69	0.68	1.29
22	4.28	1.62	0.38	2.71	1.08	1.49
25	2.00	1.50	0.75	4.55	1.82	0.82
28	4.34	2.80	0.65	4.61	1.84	1.52
30	4.40	2.81	0.64	5.86	2.34	1.20
35	3.53	3.68	1.04	8.53	3.41	1.09
40	3.88	4.04	1.04	7.46	2.98	1.35

and isolated trees (Pereira et al., 2006; Fernández et al., 2008).

However, for coffee plantations such linear model for *Kc* is limited to $L \leq 3$ as shown in figure 2. Such limitation becomes evident only after inclusion in the analysis of the results of Gutiérrez and Meinzer (1994a) obtained in drip-irrigated commercial coffee fields in Hawaii where *L* values were up to 7.5. Considering both sets of data, as *L* grew above 3, *Kc* values decreased from a peak (~ 1.05) tending asymptotically to a low value around 0.7 for $L < 6$. Due to a lack of data for the interval $3.5 < L < 5.5$ the equation $Kc = 1.8\ L^{-0.5}$ is suggested here merely as an attempt to provide an empirical description of the relationship (no statistics).

It can be inferred that the $Kc = 0.86$ for Ruiru's coffee described by Blore (1966) was probably for $L \approx 4$. This last figure can also be estimated by the empirical relationship presented below associating leaf area per plant (~26 m^2) with the number of plants per ha (2.7 m by 2.7 m ≈ 1371 plants ha^{-1}). As *L* increases above 3 part of the canopy becomes self-shaded reducing the amount of leaves exposed directly to the solar radiation reducing the transpirative power of the canopy. This effect was demonstrated experimentally in a grapevine by Williams and Ayars (2005) when a sudden artificial raise of the leaf curtain, while *L* remained the same, abruptly increased the water use from 42 L d^{-1} to over 60 L d^{-1} and *Kc* jumped from 0.9 to 1.3. Also in grapevines Netzer et al. (2009), in Israel, observed a leveling and even a small reduction in water use at $L > 4$ with a corresponding decrease in *Kc*.

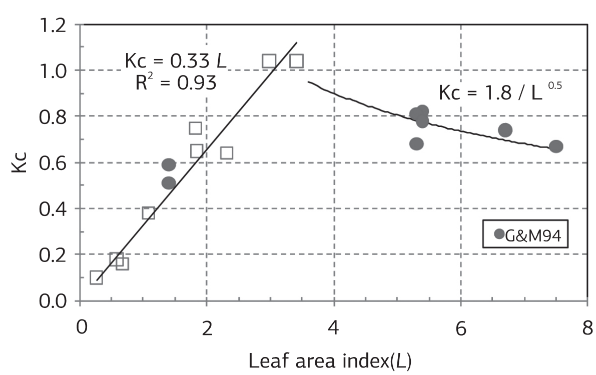

Figure 2. Coffee crop coefficient (*Kc*) as affected by leaf area index (*L*). G&M94 = results from Gutiérrez and Meinzer (1994a).

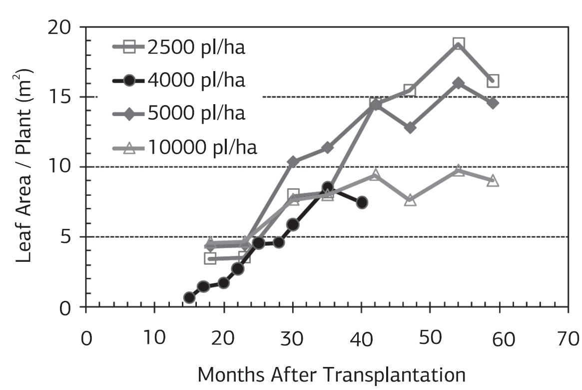

Figure 3. Time variation of the leaf area per plant of coffee plantations with different planting density. (Adapted from Valencia, 1973; including data from table 1).

For the Hawaiian coffee plantations Gutiérrez and Meinzer (1994a) found that for $L > 4$ tree transpiration became the dominant term in the water use, and that soil evaporation was negligible for $L > 6.7$. As the coffee canopy grew and shaded the ground most of the day less solar radiation reached the ground decreasing the soil evaporation and increasing transpiration. Such behavior was observed micrometeorologically in terms of energy balances along the growing season (Gutiérrez and Meinzer, 1994b). Their results show that *ETc* consumed about 40% of the available net radiation for $L < 4$, but the proportion jumped suddenly to around 60% for $L > 4$. It was concluded that the mature coffee hedgerows at high *L* behaved more like closed forest canopies than widely spaced annual crops. Indeed, results from Tausend et al. (2000) with three contrasting coffee canopy architectures indicate that aerodynamically the canopy tends to become less coupled to the atmospheric conditions as *L* approaches 4. In other words, the turbulence within the canopy decreases and weakens the interaction with the atmosphere. Such results are substantiated theoretically with numerical simulations of canopy flows showing that the aerodynamic roughness of the plant canopy decreases with increase in *L* above a threshold (Shaw and Pereira, 1982). Based on the many converging results discussed above it is here inferred that the roughness of coffee plantation decreases substantially for $L > 3$.

To become operational the present *Kc* model needs an easy way to estimate the coffee tree leaf area. Leaf areas of coffee plantations are rarely reported but a very few displaying time variations along the seasons are available for arabica cv. Caturra (Valencia, 1973), and Apoatã IAC-2258 (Villa Nova et al., 2002) and they are summarized in Figure 3. Regardless of the cultivar the leaf area growth after transplantation to the field shows the same pattern along the time. Maximum leaf area per plant tends to be reached after 3 to 5 years and it is determined by the planting density (*PD,* number of plants per ha). Data from Valencia (1973) shows that the leaf area per plant is inversely related with *PD* (2500, 5000 and 10000 plants ha^{-1}) indicating the effect of the fierce intraspecific competition for the natural resources (water, nutrients and solar radiation) among neighboring plants as the number of individuals increases in the same ground area. At 10000 plants ha^{-1} the leaf area grew up to the third year tending afterwards to stabilize between 8 and 10 m^2 per plant. Halving the coffee density (5000 plants ha^{-1}) the leaf area growth extended for another growing season but the maximum leaf area per plant did not double and reached about 15 to 16 m^2. For another 50% reduction in the number of trees (2500 plants ha^{-1}) the leaf area increased even less achieving between 16 and 19 m^2.

Considering that the maximum leaf area (LA, m^2 $tree^{-1}$) for coffee trees is reached around 60 mo-old (Figure 3) it was possible to come up the following empirical relationship of planting density (PD, plants ha^{-1}): $LA = 88.38 – 8.63 \text{ Ln } (PD)$. (Note: no statistical significance due to small number of data points). For the sake of comparisons with the restricted data set now available such equation predicts 21 m^2 for 2500, 15 m^2 for 5000, and 9 m^2 for 10000 plants ha^{-1}. For the independent sets (not used in the equation fit) it predicts 17 m^2 for 4000 plants ha^{-1}, a maximum value very close to the 15.6 ± 3.3 m^2 reported by Gutiérrez and Meinzer (1994a) for an Yellow Catuaí field. For PD = 816 plants ha^{-1} (3.5 m by 3.5 m) the predicted leaf area is about 31 m^2, a value very close to 32 m^2 (average of 7 trees) reported by Franco and Inforzato (1950) for 40-yr-old arabica cv. Bourbon at the end of the rainy season in Campinas, SP, Brazil.

Another empirical approach relating leaf area index (L) with several dimensions of the coffee canopy is reported for the cv. Apoatã IAC-2258 (see details in Favarin et al., 2002). Assuming a conical shape the canopy volume ($V = \pi\, h\, D^2/12$; h is the depth of the foliage, in m; D is canopy base diameter, in m) was a good estimator of L for the present data set ($0.27 < L < 3.4$; Table 1), i.e., $L = 0.0134 + 2.74\, V$ ($R^2 = 0.99$, n = 9). Consequently, for $L > 3.4$ ($V > 1.2$ m^3) this equation remains to be tested.

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