IMPROVING IRRIGATION MANAGEMENT BASED ON CANOPY-ATMOSPHERE COUPLING

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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 conducted experiments with five different crops (coffee, sugarcane, citrus, maize and soybean) in terms of physiology and planting arrangements to discuss the crop coefficient paradigm and its relationship with reference evapotranspiration and to highlight the needed changes on irrigation management. We found the Kc decreasing as ETo increased because 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 maize and sugarcane (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. Only soybean showed low canopy-atmosphere decoupling and because that Kc did not show the decreasing trend observed for the remaining crops, highlighting the need for computing the decoupling factor for better irrigation management.

KEY-WORDS: decoupling factor; coffee; sugarcane; citrus; maize; soybean.

APRIMORANDO O MANEJO DA IRRIGAÇÃO COM BASE NO ACOPLAMENTO COPA-ATMOSFERA

RESUMO: Os grandes avanços nas tecnologias de irrigação não foram acompanhados pelo manejo de irrigação na maior parte das áreas irrigadas. A falta de informações básicas sobre as necessidades hídricas das culturas é uma das razoes para uso inadequada da água de irrigação. Uma das abordagens normalmente utilizadas para quantificar o uso consultivo de água em culturas irrigadas é através da abordagem baseada na estimativa da evapotranspiração de referencia (ETo) em associação com o coeficiente de cultivo (Kc) para estimativa da evapotranspiração máxima do cultivo (ETc). Neste trabalho utilizou-se dados de cinco culturas (café, citros, cana-de-açúcar, milho e soja) para discutir o paradigma do Kc e sua relação com a ETo. Com exceção da cultura da soja, observou-se que o Kc decresce com a ETo devido às elevadas resistências internas da planta, que limita o transporte de massa do sistema vegetal para a atmosfera. Para cana-de-açúcar e milho, mesmo após a completa cobertura do solo pela cultura, Kc também decresceu com a ETo, destacando que essa tendência não é exclusiva de culturas de grande porte e esparsas como nos pomares de citros e cafeeiros. Apenas os dados oriundos na cultura da soja mostraram acoplamento copa-atmosfera relativamente inferior em comparação com as demais culturas, indicando a necessidade de se computar o fator de desacoplamento copa-atmosfera para a melhoria do manejo da irrigação em culturas agrícolas.

PALAVRAS-CHAVE: fator de acoplamento, café, citros, cana-de-açúcar, milho, soja.

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 our previous studies and new datasets from different crops (citrus orchard, coffee, sugarcane, maize and soybean) (MARIN et al., 2005; MARIN; ANGELOCCI, 2011; NASSIF; MARIN; COSTA, 2014, MARIN et al., 2016) 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 (McNAUGHTON; JARVIS, 1983) were considered. To do so, we used data from different crops (coffee, sugarcane, citrus orchard, maize and soybean) to discuss the crop coefficient paradigm, and to show how this irrigation management might be changed if the transpiration coupling to the atmosphere were considered.

MATERIAL E METHODS

Five experiments were conducted at College of Agriculture “Luiz de Queiroz” (ESALQ) of University of São Paulo (USP), Piracicaba, São Paulo State, Brazil (latitude 22°42′S; longitude 47°30′W; 546 m amsl) with the following crops: citrus, coffee, sugarcane, maize and soybean.

Excepting the citrus experiments, in which experiment actual crop evapotranspiration (ETc) was measured by the Bowen ratio (β) method evaluated by Perez et al. (1999). The β method is based on vertical differences of air temperature

(ΔT) and vapor pressure (Δe) by measuring as a function of the height of the crop. For the citrus experiments we used the aerodynamic method (THOM et al., 1975),

Eqs.(1) and (2) were used to estimate ETc by β method and Eqs.(3) to (7) were used for the aerodynamic method. It’s emphasizes that the variable fe of Eq.(3) is an empirical coefficient function to take in account the atmospheric stability described by Thom et al. (1975). The following equations describe this:

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

$$\beta = \gamma \frac{\Delta T}{\Delta e} \tag{2}$$

$$\mathrm{ETc} = -\rho k^2 \frac{0.622}{P}\left(\bar{z} - d\right)\left(\frac{\Delta u \Delta e}{\Delta z^2}\right)\mathrm{fe} \tag{3}$$

$$\mathrm{fe} = (1 - 16\mathrm{Ri})^{0.75} \quad \mathrm{Ri} < -0.01 \ (\text{unstable}) \tag{4}$$

$$\mathrm{fe} = (1 + 16\mathrm{Ri})^{-2} \quad \mathrm{Ri} > 0.01 \ (\text{stable}) \tag{5}$$

$$\mathrm{fe} = 1 \tag{6}$$

$$\mathrm{Ri} = \frac{g\left(\frac{\Delta\theta}{\Delta z}\right)}{T\left(\frac{\Delta u}{\Delta z}\right)^2} \tag{7}$$

where:

ETc – actual crop evapotranspiration (mm d^{-1});

Rn – net radiation at the crop surface (MJ m^2 d^{-1});

G – soil heat flux density (MJ m^2 d^{-1});

γ – psychrometric constant (kPa $°C^{-1}$);

β – Bowen ratio (dimensionless);

ΔT and Δe – air temperature (°C) and partial vapor pressure (kPa) difference between two heigths, respectively;

ρ – air density (1.26 kg m^{-3});

k – von-Karman constant (0.4);

P – local atmospheric pressure (kPa);

$\bar{z}$ – is the average between two measurements heights of wind speed (m);

d – zero plane displacement height (m);

Δu – wind speed difference between two heights (m s^{-1});

Δz – wing speed measurement height difference between two heights (m);

fe – empirical correction function (dimensionless);

Ri – gradient Richardson number (dimensionless);

g – gravitational acceleration (9.81 m s^{-2});

$\Delta\theta$ – vertical difference of potential temperature (K) set equal to ΔT as suggested by Rosenberg et al. (1983) due to small Δz used.

The daily reference evapotranspiration (ETo) was estimated based on the Penman-Monteith equation as parameterized by Allen et al. (1998) (Eq.3). The equation is as follow:

$$ETo = \frac{0.408\, s\left(Rn - G\right) + \gamma \frac{900}{T+273} u_2 VPD}{s + \gamma\left(1 + 0.34\, u_2\right)} \qquad (3)$$

where:
ETo – reference evapotranspiration (mm d^{-1});
s – slope of the saturation vapor pressure curve (kPa);
T – mean air temperature (°C);
u_2 – wind speed at 2 m height (m s^{-1});
VPD – vapor pressure deficits (kPa).

Diurnal course of leaf diffusive resistance (rs) was determined along several days in each experiment using a pre-calibrated porometer. The rs was measured on the way representative leaves of each crop from 0900 h to 1600 h (local time).

The mean values of rs were used to compute the decoupling factor (Ω) for a hipostomatous leaf, which was defined by the following equation as described by McNaughton and Jarvis (1983) (Eq.4). It's emphasizes that the bulk aerodynamic resistance (r_a) was calculated by Eq.(5).

$$\Omega = \frac{1}{1+\left[\frac{\gamma}{\left(s+\gamma\right)}.\frac{r_S}{r_a}\right]} \qquad (4)$$

$$r_a = \frac{\ln\left[\frac{\left(z - d\right)}{z_0}\right]^2}{u.k^2} \qquad (5)$$

where:
Ω – decoupling factor (dimensionless);
r_S – stomatal resistance to vapor diffusion, measured by steady state porometer (s m^{-1});
r_a – bulk aerodynamic resistance (s m^{-1});
z – height of the wind speed measurement (m);
z_0 – roughness length for momentum transfer (m);
u – wind speed (m s^{-1}).

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

RESULTS AND DISCUSSION

The actual crop evapotranspiration (ETc) and reference evapotranspiration (ETo) ratio in the whole experiment time of each crops results in a mean crop coefficient (Kc) (Figure 1). For the coffee was observed a mean Kc of 0.99, ranging from 0.6 to 1.9. For sugarcane the mean Kc observed was 1.21 ranging from 0.5 to 2.52. For citrus orchards the mean Kc was 0.24 (0.1 to 0.52) and 0.65 (0.51 to 0.94) for the winter and summer seasons, respectively. For winter maize an average Kc value observed was 1.31 (0.46 to 2.15), while summer maize presented a mean value of 0.68, ranging from 0.11 to 1.62. Also for soybean, a mean Kc value of 0.68 was observed, ranging from 0.41 to 1.09.

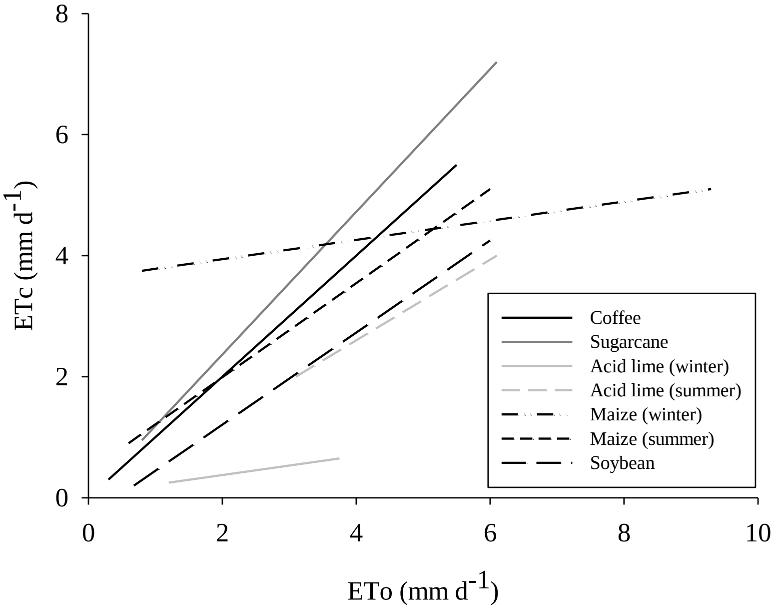

Figure 1. Relationship between coffee, sugarcane, citrus orchards, maize and soybean evapotranspiration (ETc) and reference evapotranspiration (ETo).

Excepting the soybean crop, Figure 2 shows the Kc downward trend as ETo increases for both crops, which might be a consequence of stabilization of ETc in days with ETo high atmospheric. Even during the citrus and maize cultivation in the winter season, when the atmospheric demand is relatively lower than summer season, the same trend was observed (Figure 2).

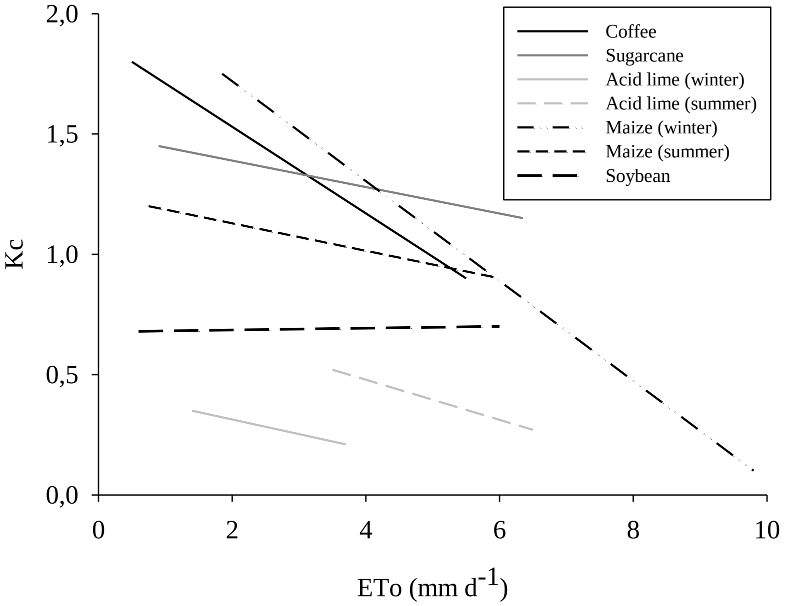

Figure 2. Relationship between coffee, sugarcane, citrus orchards, maize and soybean crop coefficient (Kc) and reference evapotranspiration (ETo).

The relationship between the ETc and ETo for both crops 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; JARVIS, 1983).

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 net radiation is the major contributor to the evapotranspiration process (McNAUGHTON; JARVIS, 1983).

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.

Based on this, Table 1 shows proposed values for Kc in different ETo ranges for the four crops. It can be observed that Kc values decreased as the ETo increased Comparing the Kc values for ETo < 2 and ETo > 4 mm d^{-1}, it decreased by 40%, 13%, 25% and 42% for coffee, sugarcane, acid lime and maize, respectively (Table 1).

Li et al. (2016) points out that the precise estimate of ETc can develop a racional irrigation scheduling and determine the correct amount of water to be applied in the area. The values of Kc presented in Table 1 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 and maize plantations.

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

Crop	ETo range	Kc	Kcb
Coffee	<2.0 mm d^{-1}	1.57 [0.84]	1.27 [0.48]
	2.0 – 4.0 mm d^{-1}	1.03 [0.23]	0.87 [0.18]
	>4.0 mm d^{-1}	0.94 [0.20]	0.67 [0.08]
Sugarcane	<2.0 mm d^{-1}	1.26 [0.46]	-
	2.0 – 4.0 mm d^{-1}	1.15 [0.27]	-
	>4.0 mm d^{-1}	1.10 [0.20]	-
Acid lime (winter)	<2.0 mm d^{-1}	0.39 [0.16]	0.46 [0.09]
	2.0 – 4.0 mm d^{-1}	0.31 [0.15]	0.35 [0.06]
	>4.0 mm d^{-1}	0.22 [0.05]	0.24 [0.03]
Acid lime (summer)	<2.0 mm d^{-1}	0.74 [0.14]	0.53 [0.11]
	2.0 – 4.0 mm d^{-1}	0.71 [0.12]	0.45 [0.03]
	>4.0 mm d^{-1}	0.68 [0.10]	0.37 [0.06]
Maize (winter)	<2.5 mm d^{-1}	1.78 [0.20]	-
	2.5 – 4.0 mm d^{-1}	1.29 [0.22]	-
	>4.0 mm d^{-1}	0.89 [0.24]	-
Maize (summer)	<2.0 mm d^{-1}	1.26 [0.48]	-
	2.0 – 4.0 mm d^{-1}	0.86 [0.53]	-

	>4.0 mm d^{-1}	0.84 [0.35]	-
Soybean	<2.0 mm d^{-1}	0.75 [0.15]	-
	2.0 – 4.0 mm d^{-1}	0.64 [0.14]	-
	>4.0 mm d^{-1}	0.70 [0.15]	-

Starting from the concept of decoupling factor (Ω), low values indicates the influence of wind speed and vapor pressure deficits (VPD) on ETc, i.e., the crop transpiration becomes conditioned by aerodynamic conditions rather than radiation conditions, which imposed a tendency of larger crop evapotranspiration rates. So, Table 2 shows the low Ω values for all studied crops, excepting soybean which presented a high value, which means that decoupled from atmospheric conditions.

Table 2. Average values of decoupling factor (Ω) for coffee, citrus orchards, sugarcane, maize and soybean plantations, under experimental conditions.

Crop	Ω
Coffee	0.09
Acid lime	0.11
Sugarcane	0.22
Maize	0.18
Soybean	0.90

According to Jarvis (1985), Ω 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 and maize, Ω was low as 0.22 and 0.18, respectively, suggesting that there was sufficient air mixing and canopy roughness for coupling the canopy to the atmosphere (Table 2).

CONCLUSIONS

Excepting for soybean, 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, sugarcane and maize 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. Canopy structure in soybean crop reduced the coupling to the atmosphere and Kc did not changed with ETo, highlighting the need to compute the decoupling factor for better crop water management.

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