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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 (Ω) 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 Ω 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 ρ is the air density (1.26 kg m^{-3}); λ 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 (Δz; 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); Δu is the wind speed difference between the two heights (m s^{-1}); Δe 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 ΔT as suggested by Rosenberg et al. (1983) due to the small Δz 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