Irrigation requirements and transpiration coupling to the atmosphere of a citrus orchard in Southern Brazil

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ABSTRACT

Crop evapotranspiration (ETc) was measured as evaporative heat flux from an irrigated acid lime orchard (Citrus latifolia Tanaka) using the aerodynamic method. Crop transpiration (T) was determined by a stem heat balance method. The irrigation requirements were determined by comparing the orchard evapotranspiration (ETc) and T with the reference evapotranspiration (ETo) derived from the Penman–Monteith equation, and the irrigation requirements were expressed as ETc/ETo (Kc) and T/ETo (Kcb) ratios. The influence of inter-row vegetation on the ETc was analyzed because the measurements were taken during the summer and winter, which are periods with different regional soil water content. In this study, the average Kc values obtained were 0.65 and 0.24 for the summer and winter, respectively. The strong coupling of citrus trees to the atmosphere and the sensitivity of citrus plants to large vapor pressure deficits and air/leaf temperatures caused variations in the Kcb in relation to the ETo ranges. During the summer, the Kcb value ranged from 0.34 when the ETo exceeded 5 mm d$^{-1}$ to 0.46 when the ETo was less than 3 mm d$^{-1}$.

1. Introduction

Brazil is the greatest citrus producer in the world. The state of São Paulo in southern Brazil produces more than 80% of Brazilian citrus. Approximately 15% of the citrus-cultivated area is under irrigation (Alves et al., 2007), whereas the remaining areas are subject to weather variability and its effects on fruit yield and quality.

Despite the advancement of technologies for water supply and the economic importance of citrus, irrigation management remains inadequate in most areas. The lack of basic information on crop water needs is one of the causes of inadequate irrigation management.

Good irrigation practices lead to higher yields and incomes for producers, but also increase the demand for water. Although water resources are reasonably available in southeast Brazil, water use for irrigation has become a major issue in this region during the winter and spring seasons when rainfall is scarce.

The crop coefficient (Kc) approach (Allen et al., 1998) for determining evapotranspiration makes it possible to consider the independent contributions of the soil evaporation and crop transpiration by splitting Kc into two separate coefficients as follows: Ke, a soil evaporation coefficient; and Kcb, a crop transpiration coefficient (referred to as the basal crop transpiration coefficient). This approach can be adopted as the procedure for scheduling and quantifying the water amount to be applied. However, few experiments have been carried out to determine the evapotranspiration for citrus orchards (Van et al., 1967; Kalma and Stanhill, 1969; Alves et al., 2007). Orchards have discontinuous soil cover and, when the plants are fully developed, they are normally tall, allowing intense air mixing in the environment. These features should be taken into account in the determination of Kc values.

In this study, we determined the values of Kc and Kcb for an acid lime orchard. We also discussed the paradigm involving the crop water requirements approach for orchard crops considering the orchard-atmosphere coupling effect on crop water requirements.

2. Materials and methods

The study was carried out in an orchard in the experimental area of the College of Agriculture “Luiz de Queiroz” at the University of São Paulo, Piracicaba, São Paulo State, Brazil (latitude 22°42’S; longitude 47°30’W; 546 m.a.m.s.l.) from January 1998 to August 2000. The micrometeorological measurements were carried out during two seasons of 2000: the wet, hot summer (January) and the dry, cold winter (July). The experimental field had 0.63 ha (63 m x 100 m) of 7-year-old plants of Citrus latifolia Tanaka grafted...
on *Citrus limonia* Osbeck rootstock growing in an orchard with the largest dimension oriented predominantly northwest and southwest. 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 (diameter).

The soil was classified as Typic Rhodustolls. On the northwest side at 50 m distance from of the citrus orchard, there was a Pinus sp. wind break. The predominant wind direction at Piracicaba was southeastern. At the south and east sides of the field, there were irrigated passion fruit and mango crops (2 m in height), nearly 5 m from the orchard edge.

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

The mean values were used to compute the decoupling factor ($\Omega$) for a hypostomatus leaf, which was defined by the following equation, as described by McNaughton and Jarvis (1983) and Jarvis (1985b):

$$\Omega = 1 + \left(\frac{2r_d}{(S/\gamma + 2r_d)}\right)$$  \hspace{1cm} (1)

where $r_d$ is the stomatal resistance to vapor diffusion, and $r_b$ is the bulk aerodynamic resistance of acid lime orchards following Landsberg and Jones (1981), with shape factor values ranging from 6.3 to 7.9.

Conceptually, the extreme values for the decoupling factor are as follows: (a) $\Omega \to 1$ as $r_d/r_b \to 0$, 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 $r_d/r_b \to \infty$, indicating complete coupling of vegetation with atmospheric vapor pressure deficit and wind speed.

In 1999, micrometeorological and sap flow measurements were taken. For these measurements, a 10-m-tall tower was positioned in the middle of the field (50 m from the crop edge in the predominant wind direction). Net radiation ($Rn$) was measured with a net radiometer (NR Lite; Kipp and Zonen, Inc.) mounted 6.5 m above the soil surface. The soil heat flux ($G$) at the surface was measured using three heat flux plates (HTF3, REBS) that were placed 30 mm below the soil surface, with two plates beneath the plant canopies and another in the inter-row space.

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, we used four aspirated copper–constantan thermocouple psychrometers (Marin et al., 2001) 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 appropriate levels of measurement (Pereira et al., 2002).

The daily ETc was calculated, recorded at 10-s intervals, averaged over 15 min and stored by a datalogger (CR7; Campbell Scientific, Inc.). The following equation was used to calculate the ETc:

$$ETc = -\rho k 0.622 \frac{\Delta u \Delta e}{\Delta z} (2 - d)^2$$  \hspace{1cm} (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); $d$ and $\Delta z$ are the average between two measurement heights and the distance between two heights, respectively (m); $d$ is the zero-plane displacement height (m), which is assumed to be $2/3$ of crop height (approximately 4.5 m) based on the reports by Stanhill and Kalma (1972) and Kalma and Fuchs (1976); $u$ 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:

$$fe = (1 - 16Ri)^{0.75} \text{ Ri } < -0.01 \text{ (unstable)}$$  \hspace{1cm} (3)

$$fe = (1 + 16Ri)^{-2} \text{ Ri } > 0.01 \text{ (stable)}$$  \hspace{1cm} (4)

$$fe = 1 \text{ - 0.01 } \leq \text{ Ri } \leq 0.01 \text{ (neutral)}$$  \hspace{1cm} (5)

$$Ri = \frac{(\Delta \theta / \Delta z)}{(T(\Delta u / \Delta z)^2)}$$  \hspace{1cm} (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 inter-row ground cover by small grass vegetation. The winter period was characterized by the decrease of regional soil moisture and by inter-row grass drying, when citrus leaves and wet soil bulbs were the main water vapor sources in the area.

The meteorological data were collected from an automatic standard weather station (CR10X; Campbell Scientific, Inc.), which was located over grass 2 km from the experimental field. They were used to compute daily values of reference evapotranspiration (ETo) based on the Penman–Monteith method, as parameterized by the FAO-56 Bulletin (Allen et al., 1998). Another identical weather station was installed inside the orchard measuring the same variables at the same time during the entire experimental period.

In parallel with the micrometeorological measurements, sap flow was measured in two trees with different crown sizes. These measurements were used 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 (diameter 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).

The daily sap flow value for each branch was 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. The 24 h integrated values of sap flow were considered as representative of the daily transpiration.
Fig. 1. Daily variation of acid lime plant transpiration (T), orchard evapotranspiration (ETc) and reference evapotranspiration (ETo) throughout the experimental period of 1999.

Table 1

<table>
<thead>
<tr>
<th>Measurement date</th>
<th>Tree 1 Leaf area</th>
<th>LAI</th>
<th>Tree 2 Leaf area</th>
<th>LAI</th>
<th>Orchard average Leaf area</th>
<th>LAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan/14/2000</td>
<td>48</td>
<td>4.5</td>
<td>99</td>
<td>5.5</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Jul/11/2000</td>
<td>64</td>
<td>5.6</td>
<td>87</td>
<td>5.5</td>
<td>4.8</td>
<td></td>
</tr>
</tbody>
</table>

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).

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 (LAI). The LA was measured on ten trees in order to compute the mean orchard LAI. The LA was determined with a LAI-2000 Canopy Analyzer (Li-Cor, Inc.) in the two seasons (Table 1). The LAI of each plant was calculated by dividing the LA by the canopy crown area projected on the ground.

3. Results and discussion

The ETo was consistently higher than the ETc in both seasons, and the T was lower than the ETc in the summer. During the winter, the ETc and T were similar for the season (Fig. 1). Gaps in Fig. 1 were due to failures in the measurement system. The contribution of the active inter-row vegetation for the overall orchard evapotranspiration may explain why ETo values were higher than T values during the summer. Because the inter-row vegetation was dehydrated and apparently without transpiration activity during the winter, the acid lime trees became the main source of water vapor, leading to the similar values of ETc and T. In both seasons, values for ETo were higher than those for ETc and T. As the evaporation of the inter-row surface was computed by the difference between T and ETc, the role of the inter-row vegetation was inferred by comparing these variables (Fig. 2). Except for a few days, Figs. 2a and 3a show that T did not follow ETo and ETc for the whole range of values, but rather that T stabilized when ETc reached 4 mm d$^{-1}$. For the winter (Figs. 2b and 3b), this relationship was not as clear as it was in the summer, as ETo and ETc were lower than in summer. Despite the poor linear relation between the T and ETc, the inter-row evapotranspiration (ETg) represented nearly 35% of the overall evapotranspiration during the summer, which become almost negligible during the winter. The difference of 8% between the T and ETc (Fig. 2b) may be attributed to measurement errors rather than any ecophysiological effect. The ratio of the overall orchard area occupied by acid lime crowns to the overall orchard area ranged between 0.35 and 0.40, which was a similar value to the T:ETc ratio observed during the summer. Based on this observation, the inter-row vegetation and trees showed similar daily transpiration rates.

The mean daily Kc values (given by the ETc and ETo ratio) during the summer was $0.65 \pm 0.11$, ranging from 0.51 to 0.94. In the winter, the mean Kc value ranged from 0.10 to 0.52 with a mean value of $0.24 \pm 0.12$. The summer Kc value compared well with other Kc values reported for humid climates (Rogers et al., 1983; Boman, 1993).
1994; Doorenbos and Pruitt, 1977; Castel et al., 1987; Allen et al., 1998), but the winter Kc values were nearly half of the Kc values reported by Allen et al. (1998) for non-ground covered orchards. The winter Kc values were also lower than those observed by Alves et al. (2007) under the same climate and soil conditions.

Assuming a measurement error of about 8%, as discussed previously (Fig. 2b), we increased the ETo and found average Kc values of 0.70 and 0.26 for the summer and winter, respectively. These corrected Kc values were still slightly lower than those observed by Alves et al. (2007), but were within a similar range reported by others (Rogers et al., 1983; Boman, 1994; Doorenbos and Pruitt, 1977; Castel et al., 1987; Allen et al., 1998).

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 (Castel, 1994; Boman, 1994; Allen et al., 1998; Alves et al., 2007). Although the Kc was originally defined for bare soil, it represents the bare soil below the citrus canopies plus inter-row water loss, which includes weed transpiration. The average Kc value was 0.23 during the summer, but it was as low as 0.02 during the winter due to the severe drought observed during the season.

The variety, root-stock, plant age and management practices are responsible for differences in the Kc and Kcb values, but the differences in micrometeorological conditions have an important role, especially regarding the atmospheric water demand (Marin et al., 2005). As mentioned before, there is evidence that Kcb values may decrease under high atmospheric water demand as verified for other horticultural species (Syversten and Lloyd, 1994; Tardieu and Simonneau, 1998) due to an opposite tendency of transpiration and stomatal movement in relation to increased air vapor pressure deficit (McNaughton and Jarvis, 1983).

The non-linear relationship between T and ETo (Fig. 3a) may be due to an increase of inner resistances to water transport of acid lime trees when subjected to conditions of high atmospheric water demand, as verified for other horticultural species (Syversten and Lloyd, 1994; Tardieu and Simonneau, 1998) due to an opposite tendency of transpiration and stomatal movement in relation to increased air vapor pressure deficit (McNaughton and Jarvis, 1983).

Fig. 4 shows the response of stomatal vapor diffusion conductance (gs) to weather variables, with gs decreasing when the atmosphere demands high transpiration rates. Based on Fig. 4, it is possible to visually detect 650 W m⁻², 27 °C and 1 kPa as gs maximal points for solar radiation, air temperature and VPD, respectively. Using these values to estimate the ETo (Allen et al., 1998), a daily rate of 4.9 mm d⁻¹ was found. This estimation was done with the assumption that the net radiation was 50% of the solar radiation and that the photoperiod was 12 h. Moreover, the estimation was carried out using the average values of wind speed and relative humidity data collected throughout the experiment (1.5 m s⁻¹ and 73%, respectively).

Despite the correlation between the air temperature and VPD and the poor correlations in Fig. 4, the decreases in gs under high atmospheric water demand leads to the assumption that trees control the transpiration as the ETo increases, which could support the use of different Kcb values for discrete ETo ranges. Table 2 shows the Kc and Kcb values for different ETo ranges. For both seasons, the Kcb values decreased as the ETo increased, which may represent a way to improve water management in orchards under localized irrigation.

The decoupling factor, Ω, (Jarvis, 1985a) was calculated using aerodynamic and canopy resistance data collected during 1998 (Fig. 5). The low values of Ω demonstrated the influence of wind
The values of Kc and Kcb for different ETo ranges; the standard deviation is found in the brackets.

<table>
<thead>
<tr>
<th>Range</th>
<th>Wet summer</th>
<th>Dry winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kc</td>
<td>Kcb</td>
</tr>
<tr>
<td>1.3 &lt; ETo &lt;= 3</td>
<td>0.72 [0.13]</td>
<td>0.46 [0.09]</td>
</tr>
<tr>
<td>3 &lt; ETo &lt;= 5</td>
<td>0.69 [0.12]</td>
<td>0.44 [0.02]</td>
</tr>
<tr>
<td>5 &lt; ETo &lt;= 6.6</td>
<td>0.67 [0.11]</td>
<td>0.34 [0.06]</td>
</tr>
</tbody>
</table>

Table 2
The values of Kc and Kcb for different ETo ranges; the standard deviation is found in the brackets.

Fig. 3A shows a linear relationship between the ETc and ETo, indicating that the decrease in the transpiration rate under high atmospheric demands was compensated by a direct response inter-row evapotranspiration rate (i.e., soil evaporation plus grass transpiration) during the summer. This compensation was based on the fact that the rate of transpiration by short vegetation and soil evaporation are normally decoupled from the atmospheric conditions because Rs is the major contributor to the evapotranspiration process (McNaughton and Jarvis, 1983). This compensation, in turn, was an effect of acid lime trees on inter-row vegetation and soil reducing the wind speed near the ground.

Allen et al. (1998) claimed that Kc values must be used under standard climatic conditions (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, crop coefficients mainly for tall crops. They also asserted that Kc tends to increase under conditions of high wind speeds and low relative humidity.

However, some aspects we observed for the lime acid orchard were different from the aspects postulated by Allen et al. (1998). First, we observed high wind speed and low air relative humidity affecting acid lime transpiration and changing Kcb as the ETo varied. Second, we observed that T did not linearly follow ETo, which resulted in a decrease in Kcb values as ETo increased. Third, the Kc values did not show the same pattern during the summer due the inter-row role, compensating the citrus transpiration when there was enough soil water (Table 2). Therefore, for tall and sparse citrus orchards using localized irrigation, such as drip and micro-sprinkler systems, it is inadequate to adopt unique values of Kcb and Kc. Finally, it should be noted that Kc has a small variation as the ETo ranges from 1.3 mm d⁻¹ to 6.5 mm d⁻¹, which is mainly due to the role of inter-row vegetation. In spite of the sparse field data available in this study, Marin et al. (2005) demonstrated the same trend in coffee in southern Brazil, and this trend may be generalized for other tall sparse horticultural crops with low Ω values after further experiments.

4. Conclusions

The mean Kc value during the summer was 0.65 and during the winter 0.24. The average Kcb values ranged from 0.41 to 0.28 for the summer and winter, respectively. The transpiration represented 35% of overall orchard evapotranspiration, a value close to the orchard area occupied by acid lime trees. The acid lime leaves reduced the stomatal conductance under high temperature, VPD and solar radiation as a consequence of the strong transpiration coupling to the atmosphere. The transpiration coupling to the atmosphere was cited as the main cause for the reduced Kcb as ETo increased. During the summer, Kc values had small variation as the ETo ranged from 1.3 mm d⁻¹ to 6.5 mm d⁻¹, which was mainly due to the role of inter-row vegetation. It was proposed that the Kcb recommendation for practical purposes may be variable in function of ETo. In this study, the Kcb values decreased nearly 40% when the ETo increased from 3 mm d⁻¹ to 5 mm d⁻¹.

References