

Determination of the crop coefficient for grafted ‘Tahiti’ lime trees and soil evaporation coefficient of Rhodic Kandudalf clay soil in Sao Paulo, Brazil

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Abstract The expansion of permanent trickle irrigation systems in Sao Paulo (Brazil) citrus has changed the focus of irrigation scheduling from determining irrigation timing to quantifying irrigation amounts. The water requirements of citrus orchards are difficult to

estimate, since they are influenced by heterogeneous factors such as age, planting density and irrigation system. In this study, we estimated the water requirements of young ‘Tahiti’ lime orchards, considering the independent contributions from soil evaporation and crop transpiration by splitting the crop coefficient ($K_c = E_{Tc}/E_{To}$) into two separate coefficients; K_e , a soil evaporation coefficient and K_{cb} , a crop transpiration coefficient. Hence, the water requirement in young ‘Tahiti’ lime (ET_y) is $ET_y = (K_e + K_{cb}) \cdot E_{To}$, where E_{To} is the reference crop evapotranspiration. Mature tree water requirement (ET_m) is $ET_m = K_{cb} \cdot E_{To}$, assuming no soil water evaporation. Two lysimeters were used; one was 1.6 m in diameter and 0.7 m deep, and the other was 2.7 m in diameter and 0.8-m deep. The first one was used to calculate evaporation and the second one was used for transpiration. E_{To} was estimated by the Penman–Monteith method (FAO-56). The measurements were conducted during a period between August 2002 and April 2005 in Piracicaba, Sao Paulo state, Brazil. The lysimeters were installed at the center of a 1.0-ha plot planted with ‘Tahiti’ lime trees grafted on ‘Swingle’ citrumelo rootstock. The trees were 1-year old at planting, spaced 7×4 m, and were irrigated by a drip irrigation system. During the study period, K_c varied between 0.6 and 1.22, and K_{cb} varied between 0.4 and 1.0. The results suggested that for young lime trees, the volume of water per tree calculated by $K_e + K_{cb}$ is about 80% higher than the volume calculated using K_c . For mature trees, the volume of water per tree calculated using just K_{cb} can be 10% less than using K_c . The independent influence of soil evaporation and transpiration is important to better understand the water consumption of young lime trees during growth compared to mature lime trees.

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Introduction

The State of São Paulo (Brazil) is one of the most important producers of citrus in the world. São Paulo has 651,000 hectares of citrus in cultivation (USDA 2005), which is about 82.4% of the country's total citrus area (Agriannual 2004). It is estimated that about 15% of this total area is under irrigation (Parsons 2005). About 65% of the irrigated citrus area uses trickle irrigation and the other 35% uses sprinkler systems (Neves et al. 2004). Recent studies indicated that there was a significant increase in the area irrigated during the last 5 years. As a consequence, competition for the limited water resources is steadily increasing. Trickle irrigation is preferred over other methods because of the shortage of water. Information is limited on citrus water requirements in the region. Therefore, improving the knowledge on factors that affect water uptake by citrus trees is essential to optimize irrigation volume and timing so that water can be used more efficiently in this area.

The expansion of the area permanently under trickle irrigation systems in Sao Paulo citrus has changed the focus from the determination of irrigation timing to a quantification of irrigation amounts. Crop coefficients (K_c) to estimate the crop evapotranspiration (ET_c) are therefore important in irrigation scheduling procedures. Previous efforts to determine water requirements have concentrated on major herbaceous crops and to a lesser extent on tree crops. For example, the FAO approach (Doorembos and Pruitt 1977) in quantifying crop water requirement has been extremely successful worldwide, because it has a good level of precision combined with ease of use and transferability to farmers. However, specific information on tree crops is limited in this FAO publication. Even the recent revision by Allen et al. (1998) in improving the estimation of reference evapotranspiration (ET_o) has not added much new information on K_c for perennial crops.

There are some fundamental differences in K_c between herbaceous crops and trees. In the case of herbaceous crops, K_c varies only seasonally and its variation is linked to easily detectable phenological stages. K_c is well defined by the initial, maximum and final values. The K_c in deciduous trees also varies seasonally, but is affected by additional factors such as canopy architecture, tree density, pruning system, crop load, irrigation method and soil surface management (Ferreles and Goldhamer 1990; Goodwin et al. 2006). Furthermore, even in mature, intensively managed orchards, a full ground cover is never reached due to horticultural factors, so that K_c is always influenced by

soil wetness to some extent. A maximum or 'full cover' K_c , while useful in herbaceous crops, is not a precise and unique number in orchards.

An estimate of ET_c for a specific crop is calculated by multiplying the reference evapotranspiration (ET_o) by a K_c specific for that crop, growth stage and growing conditions. The resulting ET_c estimates water use of a crop under local or regional climatic conditions (Allen et al. 1998).

Several researchers (e.g. Rogers et al. 1983; Castel et al. 1987; Vieira and Ribeiro 1993; Boman 1994; Martin et al. 1997; Bertonha 1997; Silva 2005; Morgan et al. 2006) established a relationship between citrus ET_c and K_c . However, the K_c values in these studies were determined by treating citrus orchards as a field of a herbaceous crop.

Adjustment of orchard K_c to use in trickle irrigation under the tree canopy has been done empirically in the past by Keller and Karmeli (1974). They proposed an equation that adjusted water use rates in total area to individual canopy cover area. However, for young trees with low-canopy cover, the K_c is strongly affected by conditions that influence soil surface evaporation (Ritchie 1972; Villalobos et al. 2000). Therefore, Allen et al. (1998) considered the independent contributions of soil evaporation and crop transpiration by splitting the K_c into two separate coefficients: K_e , a soil evaporation coefficient and K_{cb} , a crop transpiration coefficient (referred to as the basal crop transpiration coefficient). By this formulation, crop water requirement (ET_c) = $(K_{cb} + K_e) \cdot ET_o$, where ET_o is the reference crop evapotranspiration. The approach was originally developed to improve daily estimates of water use for irrigated row crops (Wright 1982), but it can equally be applied to orchards under conditions where tree water use is estimated by transpiration (T) ($T = K_{cb} \times ET_o$) and soil evaporation (E_s) ($E_s = K_e \times ET_o$). The approach of Allen et al. (1998) is a simplification of a complex physical system, whereby the water use of discontinuous canopies is considered in terms of two distinct independent sources. Shuttleworth and Wallace (1985) provided a formal analysis of the water use of coupled two-source systems. The transpiration component of orchard water use may be related to ET_o using estimates of the effective fraction of shade on the soil surface (Goodwin et al. 2006). Orgaz et al. (2006) described that ET_c of orchard under trickle irrigation has four basic components: (a) tree transpiration as a function of the tree size and the time of the year; (b) rainfall intercepted and directly evaporated from the foliage, as a function of the ground cover and the frequency of canopy wetting; (c) evaporation from the overall soil surface, which is a

function (mainly) of the time-averaged soil surface wetness of the whole orchard and of the soil shading by the canopy; and (d) evaporation from the area wetted by the emitters, which would depend on the fraction of the wetted soil surface and on the irrigation frequency. Due to the difficulty in quantifying each component separately, many studies recommend the weighing lysimeter method as a way to integrate all the components (Castel 1997; Yang et al. 2003).

Among the direct methods to measure evapotranspiration, the weighing lysimeter method is the most accurate (Howel et al. 1985; Silva et al. 1999). Information about the design and operation of this equipment can be obtained from Aboukhaled et al. (1982), Allen and Fischer (1991) and Campeche (2002).

Therefore, the objective of this study was to (a) obtain E_{Tc} and K_c from a ‘Tahiti’ lime tree (Piracicaba, Sao Paulo, Brazil) using the traditional method, considering citrus as a herbaceous crop (continuous canopies) and (b) obtain the K_{cb} as recommended by Allen et al. (1998), considering citrus as a crop of discontinuous canopies using weighing lysimeters. Another objective was to compare the water requirement estimates obtained by these two methods.

Materials and methods

Experimental area

The study was conducted during a 3-year period (August 2002–May 2005) in a 1.0-ha plot planted with ‘Tahiti’ lime trees (*Citrus latifolia* Tanaka), grafted on ‘Swingle’ [*Poncirus trifoliata* (L.) Raf. × *Citrus paradisi* Macf.] citrumelo rootstock. The trees, which were 1-year old at planting and spaced 7 × 4 m, were drip irrigated using four pressure compensated drippers of 4 l h⁻¹ discharge rate per tree. The four drippers were located 0.5 m from the trunk (total discharge is 16 l h⁻¹ tree⁻¹ with 95% uniformity). The irrigation frequency was 2 days. The orchard was located in Piracicaba, Sao Paulo state, Brazil (22°41′58″S, 47°38′42″W; elevation 511 m). Average annual temperature in the area was 21.4°C and total annual rainfall was 1,257 mm. The soil was Rhodic Kandudalf, clay texture, with 5% average slope. Plant available soil water was 0.125 m³ m⁻³. The average bulk density of the soil measured between the 0.2 and 1 m depth was 1.3 Mg m⁻³. Weed control inside and outside the lysimeter was done using mechanical and chemical methods. The orchard floor was kept clean during the experimental period. Ordinary pest control practices were performed

routinely and fertilization was done monthly as recommended by Van Raij et al. (1992).

Lysimetric and Reference evapotranspiration (ET_o) measurements

A weighing lysimeter (2.7 m diameter × 0.8 m depth) (Campeche 2002) containing one tree was installed near the center of the experimental plot. The lysimeter was packed with the same soil that was removed during excavation to install the lysimeter to the same bulk densities corresponding to each different soil layer in the surrounding field. The weight changes were sensed and transmitted through three electronic cells to a data logger at midnight daily when calm conditions prevailed (average wind <1.5 m s⁻¹). The precision of the weight measurements were about ±0.268 kg (0.0468 mm). The tree in the lysimeter was irrigated and managed like the rest of the trees in the experimental area.

Reference evapotranspiration was estimated by the Penman–Monteith Model (Allen et al. 1998). The meteorological data for the period that the study was conducted were collected by an automatic weather station (Campbell Scientific, Logan, UT, USA) located 70 m away from the orchard.

Transpiration (T) and basal crop transpiration coefficient (K_{cb})

Daily changes in the lysimeter weight were recorded and T and K_{cb} were estimated (Eqs. 1–6) taking into account the individual contributions of soil evaporation and crop transpiration by splitting K_c into two separate components, K_e (Eq. 1), a soil evaporation coefficient, and K_{cb} (Eq. 2), a crop transpiration coefficient (Allen et al. 1998).

$$K_e = \frac{E_s}{ET_o}, \quad (1)$$

where E_s is the soil evaporation, and ET_o is the reference evapotranspiration (mm);

$$K_{cb} = \frac{T}{ET_o}, \quad (2)$$

where T (mm) is water transpired from the tree (Eq. 3).

$$T = \frac{[(M_i - M_{i-1} - D - P \times A - I) - E_s]}{A_c}, \quad (3)$$

where M_i is lysimeter mass (kg); M_{i-1} is lysimeter mass the previous time (kg); D is drainage (kg); P is rainfall

(mm); I is irrigation (kg); A_c is canopy area (m^2) and E_s is the water evaporated from the soil surface. The drainage was estimated by obtaining the weight difference before and after removing the drained water from the drainage tank (Campeche 2002) that was connected to the bottom of the lysimeter. Rainfall data was collected by an automatic weather station (Campbell Scientific) located 70 m away from the orchard, and irrigation data was obtained from the time of irrigation and discharge rate of the drippers in the lysimeter and the duration of the irrigation event.

Transpiration was obtained for difference between the measures of lysimeter mass, deducted rainfall, irrigation, drainage and soil evaporation and dividing by the area of shade of the canopy as described by Goodwin et al. (2006).

The estimate of E_s is as follows (Eq. 4):

$$E_s = \frac{(E_w + E_d)}{A}, \quad (4)$$

where E_w (mm) is water evaporated from the wetted soil area, E_d (mm) is water evaporated from the dry soil and A is lysimeter cross-sectional area ($5.72 m^2$);

The E_w (Eq. 5) was estimated by a water evaporation curve of the soil (Fig. 1) obtained separately for the winter and summer as a function of days after an irrigation. This was estimated using a second weighing lysimeter (1.6 m diameter and 0.7 m in depth) containing soil and located in the orchard, as described by

Silva (2005). For the irrigation frequency of 2 days, the area wetted by each dripper (A_w) was $0.28 m^2$ for a total area of $1.13 m^2$ per tree (four drippers per tree). E_d (Eq. 6) was estimated using the evaporation curve (Fig. 1) as a function of the rainfall frequency of each month (Fig. 2), considering the dry area (A_d) inside the lysimeter to be $4.59 m^2$ ($A - A_w$). It was considered a rainfall day if rainfall were $\geq 5 mm day^{-1}$.

$$E_w = K_{e1} \times E_{To} \times A_w, \quad (5)$$

$$E_d = K_{e2} \times E_{To} \times A_d, \quad (6)$$

where $K_{e1} = 1.0$ is the evaporation Kc for the irrigation frequency of 2 days. The value is obtained from an average K_e of the first and second day after irrigation (Fig. 1); K_{e2} is evaporation Kc as a function of the rainfall frequency of each month (Fig. 2); E_{To} is reference evapotranspiration (mm); $A_w = 1.13 m^2$ is the wetted area, and $A_d = 4.59 m^2$ is the dry area inside the lysimeter.

Crop evapotranspiration (E_{Tc}) and crop coefficient (K_c)

The crop evapotranspiration was estimated by dividing the total tree water consumption (TWC) by the surface area $28 m^2$ ($7 \times 4 m^2$) allocated to each tree (Eq. 7), and the K_c by the E_{Tc}/E_{To} ratio (Allen et al. 1998).

Fig. 1 Soil water evaporation (K_e) rate as a function of time (days after rainfall or irrigation) for a Rhodic Kandiudalf, clay textured soil in winter and summer; Piracicaba, Sao Paulo, Brazil

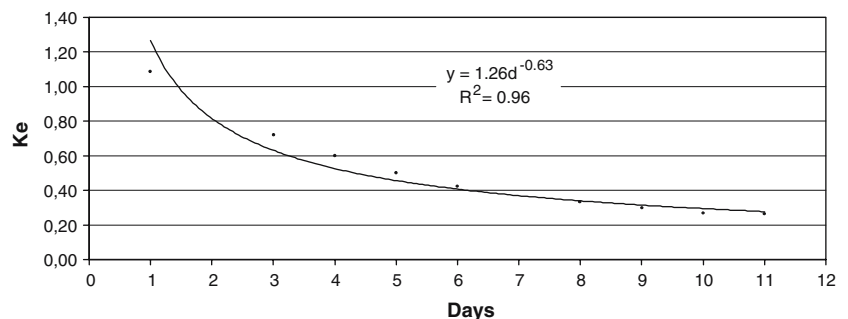
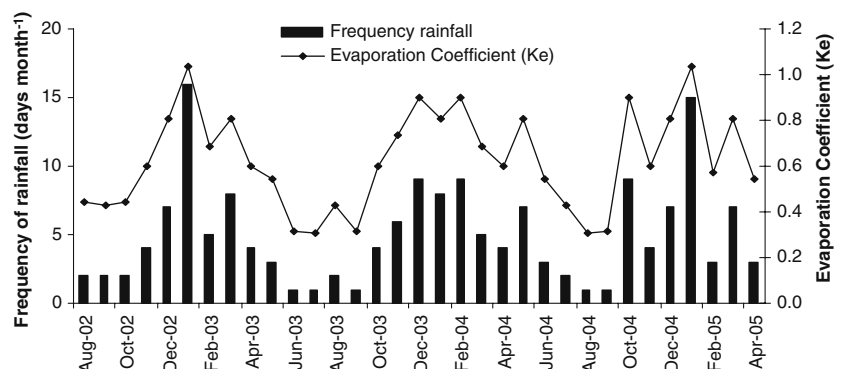


Fig. 2 Frequency of rainfall and estimated evaporation coefficient (K_e) by month during August 2002 and April 2005 in Piracicaba, Sao Paulo, Brazil. It was considered to be a rainfall day if rain was $\geq 5 mm day^{-1}$



$$ET_c = \frac{TWC}{A_t}, \quad (7)$$

where ET_c is crop evapotranspiration (mm); TWC is total tree water consumption (L) and A_t is area allocated to each tree (28 m²).

Total tree water consumption is the difference between two subsequent measures of lysimeter mass minus rainfall, irrigation and drainage occurring during the same period in the lysimeter (5.72 m²) plus the estimate of soil water evaporated from the area outside the lysimeter (22.28 m²) for a total area allocated to each tree of 28 m² (7 × 4 m²).

$$TWC = [(M_i - M_{i-1} - D - P \cdot A - I) + (Ed \times A_e)], \quad (8)$$

where TWC is the total water consumed by the tree (l); M_i is the lysimeter mass (kg); M_{i-1} is the lysimeter mass the previous time (kg); D is Drainage (kg); P is rainfall (mm); A is area of lysimeter (5.72 m²); I is irrigation (kg); Ed (mm) is water evaporated from dry soil and A_e is the area external to the lysimeter (22.28 m²), for a total area allocated to each tree of 28 m² (7 × 4 m²).

Adjustments for K_c were done empirically as recommended by Keller and Karmeli (1974). They proposed an equation (Eq. 9) that adjusted water use rates to low canopy cover.

$$K_{c_{\text{adjusted}}} = \left(\frac{ET_c}{ET_o} \right) \times \left(\frac{DC}{0.85} \right), \quad (9)$$

where DC is the coverage degree. DC is the A_c/A_t ratio (decimal). A_c is canopy coverage area (m²) and A_t is the surface area of 28 m² (7 × 4 m²) allocated to each tree.

Results and discussion

Crop evapotranspiration (ET_c) and crop coefficient (K_c)

Average daily ET_o (Table 1) ranged from a low of 2.2 mm days⁻¹ in May 2004 to a high of 5.2 mm days⁻¹ in November 2003. Daily ET_c (Table 1) was lower than ET_o in the winter (dry season) and equal to, or higher in summer (wet season). ET_c approached or surpassed ET_o between October and April through of the evaluation period (2002–2005). This is probably due to the high occurrence of rainfall and radiation during this summer period (wet season). On average (3 years), the total rainfall and the average global radiation from October to April were 1071.7 mm and 579.6 MJ m⁻² month⁻¹. Mean daily ET_c (Table 1) ranged from a low of 1.3 mm day⁻¹ in June 2003 and

1.5 mm day⁻¹ in July 2004 (winter) to a high of 4.9 mm day⁻¹ in December 2003 and 5.0 mm day⁻¹ in January and March 2005 (summer). Mean K_c (Table 1) ranged from a low 0.57 when trees were 14–18 months old (August–December 2002), 0.77 when 19–24 months old (January–June 2003), 0.69 when 25–30 months old (July–December 2003), 0.89 when 31–36 months old (January–June 2004), 0.82 when 37–42 months old (July–December 2004) and to a high of 1.22 when 43–46 months old (January–April 2005).

The citrus K_c values determined here compared closely with those measured in a humid climate by other researchers (Rogers et al. 1983; Boman 1994; Doorembos and Pruitt 1977; Castel et al. 1987). For example in FL, USA, Rogers et al. (1983) reported monthly measured ET_c/ET_o using an average of four methods for estimating ET_o (Penman, Blaney-Criddle, Jensen-Haise and pan). The resulting monthly ratios ranged from 0.9 in January (winter) to 1.11 in June (summer). Boman (1994) calculated K_c values for 5-year-old ‘Valencia’ orange trees grown in non-weighing lysimeters with water tables maintained at 0.6, 0.75 or 0.9 m from the surface. Calculated K_c values were at a minimum of 0.6 during December–February (winter) and peaked at 1.1 in June and July (summer). Castel et al. (1987) estimated monthly K_c for drip irrigated mature navels grown in Valencia, Spain. These K_c values were calculated from the average daily ET_c estimated from weekly soil water measurements by neutron probe. The values ranged from an average of 0.71 from January through July to 0.90 from August through December. In Mediterranean citrus, K_c values that were reported by Doorembos and Pruitt (1977) after adjustments for humid conditions ranged from 0.9 in March through December to 0.95 in January and February. This current study is in accordance with Martin et al. (1997), who estimated average daily ET_c values for 7-year-old ‘Redblush’ grapefruit in Arizona under arid conditions. Monthly K_c values were calculated by comparing these estimated daily values to average daily ET_o for the same period. The resulting K_c ranged from a low of 0.55–0.6 in December and January (winter) to a high of 1.1–1.2 in July (summer).

In contrast to the current study, in Sao Paulo, Vieira and Ribeiro (1993) showed $K_c = 0.8$ for mature ‘Tahiti’ acid lime tree grafted on Rangpur lime rootstock. This probably was due to the differences among varieties, rootstocks, spacing, age, soil and method of measurements. Bertonha (1997) estimated $K_c = 0.75$ for 4-year-old ‘Pera’ orange on Rangpur lime rootstock, and $K_c = 1.0$ for ‘Baianinha’ and ‘Hamlin’ orange on ‘Caipira’ orange and Rangpur lime rootstocks, respectively. Rangpur lime is a more vigorous

Table 1 Daily reference evapotranspiration (ET_o) and estimated traditional citrus evapotranspiration (ET_c) by month

Orchard age (months)		Reference ET (ET _o)				Crop ET (ET _c)			SD	(Kc)
		Maximum mm day ⁻¹	Minimum	Mean	SD	Maximum	Minimum	Mean		
2002										
14	August	4.16	1.82	3.34	0.63	2.14	1.03	1.54	0.34	0.46
15	September	5.57	1.33	3.70	1.16	2.52	0.74	1.64	0.51	0.44
16	October	6.27	3.89	5.12	0.90	3.22	0.97	2.45	0.49	0.48
17	November	5.83	2.46	4.70	0.97	3.80	1.80	3.00	0.61	0.64
18	December	6.38	2.38	4.46	1.19	5.03	2.44	3.77	0.82	0.85
2003										
19	January	5.96	2.76	4.15	1.06	5.72	3.34	4.23	0.86	1.02
20	February	5.90	1.72	4.80	1.10	4.63	1.67	3.77	0.77	0.78
21	March	5.57	3.73	4.45	0.53	4.83	3.50	4.02	0.39	0.90
22	April	4.55	2.72	3.59	0.56	3.25	2.11	2.67	0.32	0.74
23	May	3.69	1.53	2.90	0.51	2.59	1.09	1.95	0.34	0.67
24	June	3.25	2.10	2.71	0.38	1.64	0.98	1.31	0.16	0.48
25	July	4.21	1.93	3.04	0.68	1.81	1.08	1.43	0.22	0.47
26	August	4.46	1.53	3.07	0.75	2.13	0.94	1.67	0.32	0.54
27	September	5.29	1.53	3.57	1.15	2.34	0.88	1.68	0.45	0.47
28	October	5.56	3.44	4.74	0.63	3.96	2.43	3.45	0.45	0.73
29	November	6.33	4.48	5.23	0.66	5.03	3.57	4.28	0.43	0.82
30	December	5.90	3.17	4.34	1.01	6.33	3.57	4.90	1.01	1.13
2004										
31	January	6.69	1.87	4.75	1.23	5.80	1.99	4.70	1.05	0.99
32	February	6.00	3.15	4.61	0.87	6.16	3.46	4.85	0.83	1.05
33	March	5.29	3.85	4.62	0.52	4.57	3.07	3.87	0.57	0.84
34	April	3.47	1.44	2.82	0.85	2.75	1.24	2.29	0.63	0.81
35	May	3.72	1.18	2.24	0.61	3.15	1.17	2.10	0.49	0.94
36	June	3.16	0.88	2.34	0.53	1.99	1.20	1.63	0.23	0.70
37	July	3.29	0.79	2.48	0.64	1.91	0.67	1.47	0.33	0.59
38	August	4.52	1.35	3.32	0.68	2.33	1.00	1.65	0.36	0.50
39	September	5.49	1.95	4.30	0.86	3.00	1.26	2.43	0.39	0.56
40	October	5.36	0.32	3.35	1.59	6.12	1.09	3.79	1.38	1.13
41	November	6.19	1.18	4.23	1.49	5.35	1.25	3.80	1.15	0.90
42	December	6.19	1.71	4.03	1.25	7.01	2.69	5.05	1.06	1.25
2005										
43	January	6.14	1.20	3.49	1.49	7.95	1.83	4.99	1.70	1.43
44	February	6.31	2.87	4.94	0.79	5.58	3.45	4.70	0.59	0.95
45	March	5.40	1.59	3.60	1.15	6.49	2.07	5.04	1.09	1.40
46	April	4.82	0.88	3.68	1.01	5.10	2.44	4.06	0.78	1.10

rootstock than Swingle citrumelo rootstock, which was used in this current study. The data in this current study differs from the orange Kc estimated by Bertoinha (1997) probably because lime trees show higher ET_c (up to 10–20%) compared to other citrus because of their year-round growth and production, as described by Doorembos and Pruitt (1977), Morton (1987) and Wright (2000).

Transpiration (T) and basal crop transpiration coefficient (K_{cb})

Figure 1 shows the soil water evaporation curve ($K_e = 1.26 \text{ day}^{-0.63}$ and $R^2 = 0.95$). Low- and high-soil evaporation coefficient (K_e) coincided with the rainfall

magnitude, i.e. when rainfall was low, K_e was low, and when high the coefficient was high. Figure 2 shows monthly rainfall values and K_e. K_e ranged from a low of 0.31 (July 2003 and August 2004) to a high of 1.04 (January 2003 and 2005). These values of K_e coincided with low frequency of rainfall (winter) with only 1 day of rainfall per month, and high-frequency rainfall (summer) with 16 days of rainfall per month, respectively.

Mean daily transpiration (T) (Table 2) ranged from a low of 0.87 mm day⁻¹ (K_{cb} = 0.26) in August 2002 (young tree) and 0.86 mm day⁻¹ (K_{cb} = 0.38) in May 2004 (winter) to a high of 4.39 mm⁻¹ (K_{cb} = 1.09) in December 2004 (summer) and 4.43 mm day⁻¹ (K_{cb} = 1.21) in April 2005 (mature tree). Similar

Table 2 Canopy area and daily estimated citrus transpiration by month

Orchard age (months)		Canopy area m ²	Transpiration (T)			SD	Kcb
			Maximum mm day ⁻¹	Minimum	Mean		
2002							
14	August	2.20	2.42	0.06	0.87	0.80	0.26
15	September	2.50	6.33	0.09	1.87	1.91	0.50
16	October	2.90	6.60	0.17	1.74	1.76	0.34
17	November	3.40	4.66	0.10	1.83	1.22	0.39
18	December	3.80	5.87	0.34	2.91	1.50	0.65
2003							
19	January	3.85	3.49	0.48	1.51	1.06	0.36
20	February	3.97	5.84	1.84	3.36	1.08	0.70
21	March	4.15	3.54	1.80	2.57	0.61	0.58
22	April	4.22	3.62	0.88	2.63	0.82	0.73
23	May	4.33	3.82	1.28	2.25	0.78	0.78
24	June	4.90	3.04	1.07	2.20	0.52	0.81
25	July	5.30	2.89	1.77	2.20	0.28	0.73
26	August	5.72	2.73	0.68	1.43	0.54	0.47
27	September	5.83	3.50	1.38	2.21	0.66	0.62
28	October	5.90	4.05	1.39	2.54	0.70	0.54
29	November	6.10	3.39	0.91	2.36	0.85	0.45
30	December	6.25	5.21	2.76	3.71	0.67	0.86
2004							
31	January	6.50	4.97	1.29	3.24	0.95	0.68
32	February	7.15	3.78	1.69	2.61	0.49	0.57
33	March	7.90	3.32	1.23	2.48	0.66	0.54
34	April	8.40	2.38	1.17	1.84	0.40	0.65
35	May	8.95	1.32	0.48	0.86	0.28	0.38
36	June	9.20	1.33	0.45	0.88	0.28	0.38
37	July	9.50	1.83	0.41	1.03	0.34	0.42
38	August	9.72	2.85	0.56	1.54	0.67	0.46
39	September	9.85	3.90	1.70	2.73	0.54	0.63
40	October	10.10	4.05	0.94	2.13	0.76	0.64
41	November	10.30	5.71	1.10	3.29	0.97	0.78
42	December	10.40	6.35	2.83	4.39	0.97	1.09
2005							
43	January	10.90	4.74	1.14	2.99	0.96	0.86
44	February	11.05	5.93	2.73	4.52	0.85	0.92
45	March	11.28	5.83	1.64	4.10	0.99	1.14
46	April	11.85	6.86	1.01	4.43	1.38	1.21

results in the seasonal variation in evapotranspiration of citrus were observed also by Castel (1997), Yang et al. (2003) and Silva (2005).

Mean Kcb (Table 2) ranged from a low of 0.43 when the tree was 14–18 months old (August–December 2002), 0.66 when the tree was between 19 and 24 months old (January–June 2003), 0.61 when the tree was 25–30 months old (July–December 2003), 0.53 when the tree was 31–36 months old (January–June 2004), 0.67 when the tree was 37–42 months old (July–December 2004) and to a high of 1.03 when the tree was 43–46 months old (January–April 2005).

Castel (1994) found that Kcb could be 0.25 and 0.31 for young ‘Clementina de Nules’ trees (*Citrus Clementina*, Hort ex. Tan.) on Carrizo citrange

(*Citrus sinensis*, Osb. X *P. trifoliata*, Raf.) grown in Valência-Spain. Boman (1994) in FL, USA found that Kcb was 0.26 for young citrus trees. Allen et al. (1998) in Bulletin FAO-56 recommended values of 0.40–0.50 for citrus Kcb. The Kcb values estimated from the current study (Table 2) were higher than the Kcb values reported by Castel (1994), Boman (1994) and Allen et al. (1998). This may be probably due to the different methodologies adopted by these authors.

Boman and Parsons (2002) related the water use from a citrus tree to be about 3.8 l day⁻¹ during the first 2 years after planting. When compared with the results from the current study (Table 2), the volume of water estimated above is sufficient to satisfy the demands of

tree transpiration. The volume of water estimated by Boman and Parsons (2002) is in accordance with the values of transpiration measured in the current study (Table 2). Table 3 shows that the mean daily tree transpiration were 4.7, 11.4, 20.1 and 46.5 l day⁻¹ during the second, third, fourth and fifth year of trees in

the field. Similar results are related by Marin et al. (2002). He found the daily transpiration for mature trees to be about 36 l day⁻¹ during the winter. Therefore, the results suggest that the use of Kc of 0.6–0.7 (Table 3) obtained in this study (by a traditional method) and also related by Doorembos and Pruitt

Table 3 Canopy area, crop transpiration coefficient (Kcb) and traditional crop coefficient (Kc), transpiration and irrigation volume estimated for Kcb + Ke, Kc, Kc_{adjusted}, and Kcb

Orchard age (months)	Kcb	Kc	ETo (mm)	Canopy area (m ²)	Water volume for tree under canopy (l tree ⁻¹ day)				Transpiration	
					(Kcb + Ke) ^a	Kc ^b	Kc ^c (adjusted)	Kcb ^d		
2002										
14	August	0.26	0.46	3.34	2.20	7.79	3.39	8.64	1.91	2.55
15	September	0.50	0.44	3.70	2.50	12.06	4.11	10.88	4.66	3.51
16	October	0.34	0.48	5.12	2.90	16.94	7.12	17.47	5.06	3.65
17	November	0.39	0.64	4.70	3.40	19.02	10.18	18.80	6.23	5.23
18	December	0.65	0.85	4.46	3.80	24.60	14.34	19.94	11.05	8.83
2003										
19	January	0.36	1.02	4.15	3.85	18.61	16.29	18.80	5.83	8.56
20	February	0.70	0.78	4.80	3.97	28.58	14.95	22.42	13.34	11.89
21	March	0.58	0.90	4.45	4.15	25.44	16.66	21.73	10.66	8.95
22	April	0.73	0.74	3.59	4.22	23.20	11.26	17.82	11.08	10.62
23	May	0.78	0.67	2.90	4.33	19.81	8.46	14.77	9.76	9.27
24	June	0.81	0.48	2.71	4.90	21.42	6.41	15.62	10.79	10.83
25	July	0.73	0.47	3.04	5.30	24.57	7.59	18.96	11.68	11.65
26	August	0.47	0.54	3.07	5.72	22.22	9.53	20.66	8.18	7.64
27	September	0.62	0.47	3.57	5.83	29.51	9.78	24.49	12.86	11.87
28	October	0.54	0.73	4.74	5.90	37.35	20.34	32.90	14.98	11.93
29	November	0.45	0.82	5.23	6.10	39.92	26.11	37.53	14.40	14.33
30	December	0.86	1.13	4.34	6.25	44.90	30.60	31.91	23.20	19.76
2004										
31	January	0.68	0.99	4.75	6.50	45.76	30.55	36.32	21.06	20.00
32	February	0.57	1.05	4.61	7.15	45.01	34.66	38.78	18.64	18.71
33	March	0.54	0.84	4.62	7.90	48.81	30.54	42.94	19.61	15.10
34	April	0.65	0.81	2.82	8.40	34.41	19.27	27.87	15.46	19.66
35	May	0.38	0.94	2.24	8.95	23.70	18.76	23.59	7.67	8.79
36	June	0.38	0.70	2.34	9.20	25.34	15.02	25.33	8.12	9.30
37	July	0.42	0.59	2.48	9.50	28.64	13.97	27.72	9.79	9.27
38	August	0.46	0.50	3.32	9.72	40.79	16.00	37.97	14.97	14.95
39	September	0.63	0.56	4.30	9.85	60.77	23.89	49.83	26.89	26.86
40	October	0.64	1.13	3.35	10.10	48.62	38.28	39.81	21.56	20.31
41	November	0.78	0.90	4.23	10.30	68.79	39.17	51.26	33.93	32.45
42	December	1.09	1.25	4.03	10.40	79.15	52.52	49.31	45.62	45.99
2005										
43	January	0.86	1.43	3.49	10.90	63.06	54.38	44.75	32.62	33.79
44	February	0.92	0.95	4.94	11.05	93.64	51.96	64.22	49.97	50.05
45	March	1.14	1.40	3.60	11.28	78.71	56.80	47.77	46.23	47.68
46	April	1.21	1.10	3.68	11.85	87.44	48.12	51.30	52.55	54.58

^a Volume (V) = $[(K_e \times A_w \times ETo) + (Kcb \times ETo \times A_c)]$

^b $V = Kc \times ETo \times A_c$

^c $V = Kc \times ETo \times A_t$

^d $V = Kcb \times ETo \times A_c$

A_w is the wetted area, A_c is the canopy coverage area and V is calculated considering $A_w = A_c$; A_t is the surface area 28 m² (7 × 4 m²) allocated to each tree; ETo is the reference evapotranspiration, Kc is the crop coefficient; Kcb is the transpiration crop coefficient; $K_e = 0.8$ is the evaporation crop coefficient for an irrigation frequency of 4 days. Value of K_e was obtained from an average K_e of the first, second, first and fourth day after irrigation (Fig. 1)

(1977), or the use of a water volume of 3.8 l day^{-1} per tree as described by Boman and Parsons (2002), is not sufficient to satisfy the water requirement of young citrus trees during the first years in field. The canopy cover of young trees is not sufficient to shade the total wetted area. Hence, soil evaporation is high. An additional amount of water should be applied to supplement the soil evaporation. This additional amount of water depends on the wetted area and the irrigation frequency (Fig. 1). Table 3 shows that the volume of water per young tree as calculated by $K_{cb} + K_e$ (considering high soil evaporation in the wetted area) is about 60% higher than the volume of irrigation calculated using only the traditional K_c . The water volume calculated (Table 3) considering high soil evaporation ($K_{cb} + K_e$) is in accordance with the water volume calculated for young trees by $K_{c, \text{adjusted}}$ (Table 3), as described by Keller and Karmelli (1974). Similar water volumes are recommended by Coelho et al. (2004). He recommends volumes of 10, 15, 25, 45 and 65 l day^{-1} per citrus tree, during the first, second, third, fourth and fifth years, respectively. The growth of young citrus trees is strongly affected by water deficit during the first years after planting (Castel and Buj 1992; Castel 1993; Alves Jr. et al. 2005). Therefore, the results showed that consideration of the independent contributions of soil evaporation and young tree transpiration is important in determining the total water requirements for irrigating young trees.

Boman and Parsons (2002) estimated that in Florida, the water requirement for a 6-year-old ‘Valencia’ tree was about 40 l day^{-1} (57 and 20 l day^{-1} in the summer and winter, respectively). Similar results were found by Coelho et al. (1994) in Brazil. He suggested that high ‘Tahiti’ lime crop yields were obtained when trees were drip irrigated with about 30 l day^{-1} . The results related by Coelho et al. (1994) are in accordance with water volume calculated by K_{cb} estimated in this current study (Table 3). Therefore, the results suggest that the use of only K_{cb} in mature trees can be sufficient to satisfy the water requirement.

The water volume used by mature trees calculated by K_c and $K_{c, \text{adjusted}}$ had a similar value (about $52 \text{ l tree}^{-1} \text{ day}^{-1}$). A lower mature tree water use was found using K_{cb} (about $45 \text{ l tree}^{-1} \text{ day}^{-1}$) (Table 3). The calculated K_{cb} volume of water used was 15% less than that predicted by K_c and $K_{c, \text{adjusted}}$. In contrast to the current study, Coelho et al. (2004) recommended a water volume of 100 l day^{-1} per mature citrus tree. Coelho et al. (2004) probably considered a high soil evaporation under the tree canopy, similar to the water volume calculated by $K_{cb} + K_e$ in the present study.

Therefore, the results showed that the contribution of soil evaporation and tree transpiration should be considered in determining the trickle irrigation rates necessary for optimum ‘Tahiti’ lime tree growth.

Conclusions

The independent influence of soil evaporation and transpiration is important to better understand the water consumption of young lime trees, during the early stage of growth, and in mature lime tree. For young lime trees, the volume of water per tree calculated by $K_{cb} + K_e$ is about 60% higher than the volume calculated using K_c . For mature trees, the volume of water per tree calculated using just K_{cb} can be 10% less than using K_c .

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