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Water balance and crop coefficient estimation of a citrus orchard in Uruguay

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Abstract

The actual evapotranspiration (ETc) of mature 'Valencia' orange trees [*Citrus sinensis* (L.) Osb.], drip-irrigated and non-irrigated, was calculated using the water balance method, over three years. Annual ETc was 24% higher from irrigated trees that from non irrigated trees (767 and 620 mm year^{-1}, respectively). Maximum monthly average ETc was 3.3 mm day^{-1} or 80 L tree^{-1} day^{-1} (trees were spaced at 6 × 4 m). Generally ETc rate was reduced in January, the month of maximum atmospheric demand, compared with December, even under fully irrigated trees. The average annual value of the crop coefficient (Kc) for irrigated trees was 0.69. Monthly Kc values also showed a clear seasonal trend, with minimum values in summer (0.60), intermediate values in autumn and spring (0.77 and 0.80, respectively) and maximum values in winter (0.87). These values provide a useful base for the design and operation of micro-irrigation systems, for mature citrus trees in Uruguay.

Additional key words: evapotranspiration, irrigation, micro-irrigation, 'Valencia' oranges, water mass balance.

Resumen

Balance hídrico y estimación del coeficiente de cultivo en un huerto de cítricos en Uruguay

Se estimó la evapotranspiración real de árboles de naranjo 'Valencia' [*Citrus sinensis* (L.) Osb.], sin riego y regados por goteo, mediante la metodología del balance hídrico, durante tres años. La ETc fue 24% mayor en los árboles regados que en los de secano (767 y 620 mm anuales, respectivamente). La evapotranspiración media en el mes de máxima demanda fue de 3,3 mm día^{-1} ó 80 L árbol^{-1} día^{-1} (para un marco de plantación de 6 × 4 m, 24 m^2). Se repitió sistemáticamente que la tasa de ETc tuvo un descenso en enero, mes de máxima demanda atmosférica, comparado con diciembre, aún en los árboles bien regados. El coeficiente de cultivo (Kc) promedio anual para los árboles regados fue 0,69. Se encontró un claro y sistemático comportamiento estacional, con valores mínimos del Kc en verano (0,60) intermedios en otoño y primavera (0,77 y 0,80, respectivamente) y máximos en el invierno (0,87). Estos valores deberían ser la base para el diseño y la operación de sistemas de riego localizado para explotaciones de cítricos adultos en Uruguay.

Palabras clave adicionales: balance de agua, evapotranspiración, naranjos 'Valencia', riego, riego localizado.

Introduction

Knowledge of evapotranspiration is essential for efficient water management. Accurate predictions are needed, in order to adjust irrigation volume, and frequency to crop water demand, to design irrigation systems, and in water right use disputes. Unfortunately, measurements of evapotranspiration from mature trees are not abundant. This data scarcity is mainly caused by tree size and by the long time needed to obtain good estimates (Hoffman *et al.*, 1982; Castel *et al.*, 1987).

With regard to different methods used to measure evapotranspiration water balance has been one of the most widely used methods in tree crops. Crop evapotranspiration (ETc) is estimated from soil water variation, rainfall, irrigation, runoff and net drainage under the root zone. Variation in soil water is usually determined by neutron probe, TDR or by capacitance probes. Net drainage is the difference between deep percolation minus capillary rise. A possible way of estimating it is through the «zero flux plane» method, using tensiometer

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readings, plus a neutron probe (Castel *et al*., 1987). However its determination is difficult and inaccurate, especially under drip irrigation.

In the water balance method, the error in estimation of the different terms is accumulated in ETc, and therefore the estimates are not very precise, which is the main disadvantage of the method.

Another constraint is the spatial variation in soil moisture, especially under drip irrigation, where tridimensionality is an added problem. Further, ETc estimations can only be made for relatively long time intervals of about a week or longer.

Most earlier research on evapotranspiration in citrus was based on changes in the soil water content under low frequency flood (Smajstrla *et al.*, 1982; Castel *et al*., 1987) or sprinkler irrigation (Koo, 1961; Kalma and Stanhill, 1969). However, there are recent reports on the use of this technique to estimate ETc in micro-irrigated citrus and other fruit trees (Sharples *et al.*, 1985; Moreno *et al*., 1988; Sepaskhah and Kashefipour, 1995; Andreu *et al*., 1997).

The water balance (WB) method has been widely used in citrus (Koo and Sites, 1955; Koo, 1961; Kalma and Stanhill, 1969; Hoffman *et al*., 1982; Smajstrla *et al*., 1982; Wiegand and Swanson, 1982; Sharples *et al*., 1985; Castel *et al*., 1987; Metochis, 1989; Castel and Buj, 1990, 1993; Morgan, 1992; Durán, 1993; Sepaskhah and Kashefipour, 1995; Fares and Alva, 1999; Grismer, 2000) and in other crops (McGowan and Williams, 1980; Vachaud *et al*., 1985; Moreno *et al*., 1988; Andreu *et al*., 1997).

The two components of the WB method that can be measured with a higher level of confidence are irrigation input and variation in soil water content. With regard to the last parameter the results of McGowan and Williams (1980) with rain fed wheat (*Triticum aestivum* L.) should be considered. These authors found large variation in changes of stored soil water, measured in profile replicates. This was mostly due to spatial heterogeneity of rainfall distribution in the soil, as well as variation due to drainage and root water extraction. This variation requires special attention to be paid to replication and location of neutron probe access tubes, when evapotranspiration is being estimated at a site. Further, this variation is normally greater under drip irrigation, due to the non uniform water distribution both on the surface and at depth.

Different authors have done weekly to monthly readings, used one to 38 access tubes and measured one to 15 trees (Koo, 1961; Kalma and Stanhill, 1969; Sharples *et al.*, 1985; Moreno *et al*., 1988; Sepaskhah and Kashefipour, 1995; Andreu *et al*., 1997; Fares and Alva, 1999).

On the other hand the two components determined with greater uncertainty are effective rainfall and drainage. The uncertainty regarding the true magnitude of these parameters increases with increased rainfall.

Castel and Buj (1990) considered effective rain was all rain of less than 40 mm week^{-1}, while Domingo *et al.* (1996) considered effective rain was rain over 5 mm day^{-1} and less than 30 mm week^{-1}.

Morgan (1992) suggested that as runoff and percolation are difficult to measure, evapotranspiration should be calculated only in periods of relatively little rainfall. Vachaud *et al*. (1985) proposed that the WB method was not appropriate to estimate ETc, when there was enough rainfall to produce runoff. Koo (1961) only used periods with less than 3 mm of rainfall week^{-1}, to reduce possible errors in drainage estimation.

The objectives of this work were to estimate actual crop evapotranspiration by the water balance method, in a typical mature citrus tree orchard, and from it, calculate the crop coefficient (Kc) and generate information for the proper agronomic design and management of micro-irrigation.

Material and Methods

The experiment was carried out over three seasons (1997 to 2000) at the farm «Quinta Nº 7» belonging to Milagro SA. The farm is located at Kiyú (34º 39' South, 56º 46' W, at 30 m ASL), San José, Uruguay. It was selected an experimental plot and planted during winter 1981 with orange trees [*Citrus sinensis* (L.) Osb.] cv 'Valencia' grafted onto trifolia rootstock [*Poncirus trifoliata* (L.) Osb.] at a spacing of 6 × 4 m.

The trees were about 3 m height throughout the experiment, and they covered about 30% of the ground at the start and 50% at the end of the experiment.

Drip irrigation was applied daily, during the whole irrigating season, with pressure compensated emitters of 4 L h^{-1} placed every meter on a single line per tree row. There were a total of four drippers per tree. The drippers wet a continuous fringe of about 1 m width measured at 0.30 m depth. The irrigation applied covered 100% of crop evapotranspiration. The ETc was estimated using a Class «A» evaporation pan and the corresponding pan coefficient (Kp) and Kc for mature citrus trees proposed by the FAO (Allen *et al*., 1998).

Table 1. Total rainfall, reference evapotranspiration (ETo) and irrigation amount (mm) and irrigation start and end dates in each season

Season	Rainfall	ETo	Irrigation		
			Start	End	Amount
1997/98	1,311	954	Nov 10	April 15	146
1998/99	1,362	1,046	Oct 8	March 26	234
1999/00	1,319	1,196	Sep 23	March 24	372

Trees receiving more than 100% of ETc, yielded only 93% (García Petillo and Castel, 2004). It was considered that water supply was not limiting.

The main meteorological and irrigation data during the experimental period are shown in Table 1.

According to the Uruguayan classification, the soil was a *Brunosol Subéutrico Lúvico* (equivalent to a typical Argiudoll (Durán *et al.*, 2005) of the Kiyú unit, with a 0.25 m clay-silt loam horizon followed by a Bt clay-lime horizon down to 0.70 m. The orange grove was on a flat terrain with negligible slope.

Weed control was by herbicides applied in 1.5 to 2 m borders on each side of the tree row. The inter rows were in pasture, mainly spontaneously generated grasses, which were mown periodically to control its height. This is a common management method in citrus crops in Uruguay. A detailed description can be found elsewhere (García Petillo and Castel, 2004).

Water balance (WB)

The evapotranspiration of two trees, one in a non irrigated plot (NI) and the other in an irrigated plot (IRR), was estimated using the mass balance equation:

$$ETc = P_{ef} + Irr - D + \Delta S \qquad [1]$$

$$\Delta S = \left(\sum_{i=1}^{n} \left(\Theta_1 - \Theta_2 \right) \right) \Delta z_i \qquad [2]$$

where ETc = crop evapotranspiration during the study period (mm), P_{ef} = effective precipitation (mm); Irr = irrigation (mm); D = drainage (mm); ΔS = variation in the soil water storage during the study period (mm); Θ_1, Θ_2 = volumetric water content from a soil horizon, in two consecutive measurements ($cm^3\ cm^{-3}$); Δz_i = thickness of each soil horizon (dm); n = number of horizons in the soil profile.

As there were two different situations from the evapotranspiration point of view in our conditions, two separate balances were estimated:

a) In the area effectively used by the tree, a border of 2 m at each side of the row, determining an area of 16 m^2 for each tree (from now «row»).

b) In the between row area a 2 m wide, grass border where there is less orange tree root development. The main purpose of this area is transit, for plant protection purposes and harvest (from now «between rows»).

Evapotranspiration in the plant spacing (6 × 4 m) was estimated as the weighed sum of ETc in both areas, following a similar approach to Andreu *et al.* (1997). They divided the planting space into an area of main root activity, coincident with the dripping edge of the tree top, and an area outside that one, with lower root activity.

The capillary rise was considered negligible in the mass balance equation. Observations with a piezometer overall the experiment showed that the freatic level was always at least 7 m deep. Working on sandy soils, Fares and Alva (1999) also considered the capillary rise to be nil as their freatic level was more than 3 m deep. The same criteria were used by Kalma and Stanhill (1969) with a freatic level at a depth of 30 m.

Effective precipitation

Total precipitation (P_t) was registered hourly with an electronic pluviograph installed at the farm. Given that the average soil infiltration rate is approximately 5 mm h^{-1} (based on previous measurements at this farm; unpublished data) all rain which was not greater than this intensity was considered effective (P_{ef}). Where rainfall was more intense than this only 5 mm h^{-1} were considered. It was assumed that the rest was runoff.

In periods where total rainfall was very high (more than 30 mm $week^{-1}$), the assumption that soil infiltration rate is still 5 mm h^{-1} can not be sustained. This is because it gets to be a saturated regime. In those cases, ETc was not calculated. This threshold value compares with that of Castel and Buj (1990), who considered all rain was effective if it was less than 40 mm $week^{-1}$.

Domingo *et al.* (1996) considered effective rainfall was over 5 mm day^{-1} and less than 30 mm $week^{-1}$.

The other factor to be considered is direct rain interception (I) by the canopy. For this, the Kalma *et al.* (1968) criteria were followed, given that the orange trees studied were of similar size, age and plant spacing as theirs. They found that the threshold value of rain interception by mature 'Shamouti' orange trees, above which stem flow occurred, was 2.3 mm.

In the row the interception was calculated as:

$$I = 2.3\ \text{mm} \times \text{area covered by the tree canopy } (m^2) / 16 (m^2) \quad [3]$$

The area covered by the canopy was taken as the average value between two consecutive measurements, calculated as the vertical projection of the ellipsoid, calculated from both perpendicular diameters of the treetop.

To perform the balance, the criteria were:

a) If $P_t - P_{ef} > I \Rightarrow P_{ef}$ corrected $= P_{ef}$ [4]

b) If $P_t - P_{ef} \leq I \Rightarrow P_{ef}$ corrected $= P_{ef} - I$ [5]

That means that only when total precipitation was almost all effective, was it corrected by interception. In the other case, effective precipitation was not corrected, meaning that interception reduced the non-effective precipitation (runoff).

Irrigation

Water, applied by irrigation, was determined weekly by a water meter placed in the central row of the plot where the evaluated tree was located.

Variation in the soil water content

Soil water content was measured with a neutron probe. It was a CPN model 503DR HYDROPROBE, with a neutron source of 1.85 GBq (50 mCi) Americium-241:Berilium and 50 mm head. The criteria of many authors (Kalma and Stanhill, 1969; Andreu *et al.*, 1997; Ladekarl, 1997; Annandale *et al.*, 2003) were followed. There was a preference for a high level of instrumentation for a single tree, instead of having more replicates of trees with less instrumentation. Thus, two grids of access tubes were installed to a depth of 1.2 m. One was installed in the square of a no irrigation (NI) tree and the other in the square of an irrigated at 100% of estimated ETc (IRR) tree.

At the NI tree 9 access tubes were installed. They were spaced 1 m apart in a rectangular grid. In the IRR tree 25 access tubes were installed. They were spaced at 0.50 m. The layout of both grids is shown in Figure 1.

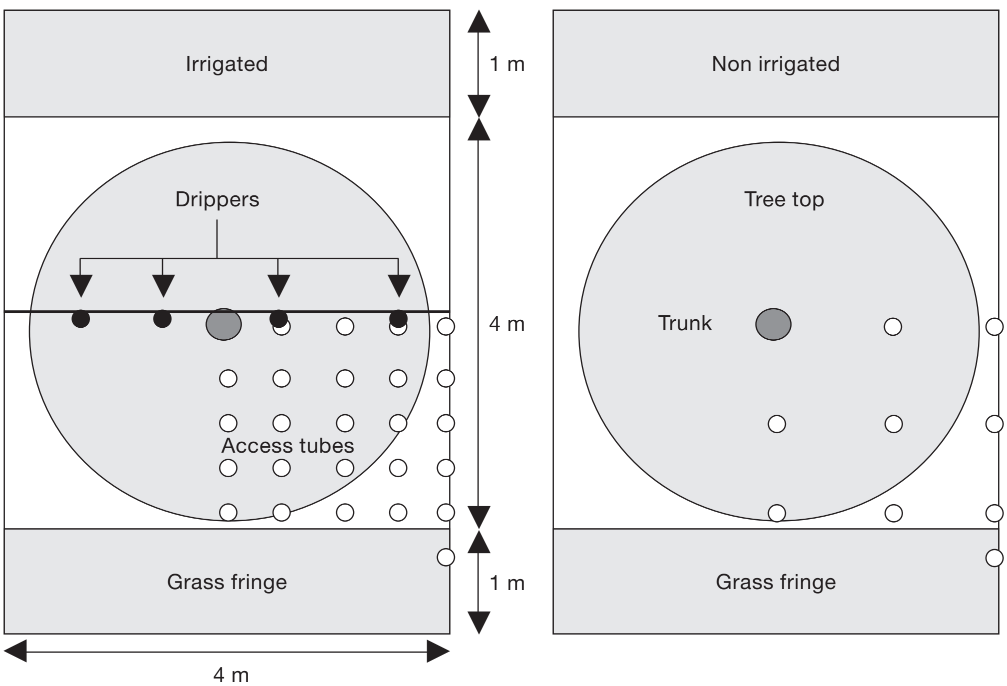


Figure 1. Scheme of neutron probe access tube placement, for irrigated and non irrigated trees. The tree top projection shows the approximate average size for the whole experiment.

The neutron probe was calibrated against volumetric soil water content for each of four soil horizons, at 0.15, 0.30 and 0.50 m for the three upper horizons, and at 0.70, 0.85 and 1.00 m for the lower one. To do that, readings were taken (standard and number of counts) and unaltered soil samples were extracted (9 to 14 in each horizon) to determine the gravimetric water content. The volumetric soil water content ranged from 16 to 47%.

Linear regression equations were adjusted, and all of them were significant ($p < 0.01$) with a R^2 between 0.82 and 0.87.

During periods with no irrigation, under the IRR tree only the 9 access tubes, placed in the same position as the NI ones were measured.

In both cases weekly readings were performed, taking a standard reading of 4 min and count readings of 30 s, from 27 May 1997 to 24 March 2000, at soil depths of 0.15, 0.30, 0.50, 0.70 and 1.00 m. The readings at 0.70 and 1.00 m were used to estimate drainage (see next paragraph).

To estimate the water content in the main soil profile (0-60 cm), the reading at 15 cm was considered representative of the upper horizon (0-25 cm), the reading at 30 cm representative of the 25-40 cm horizon. The reading at 50 cm represented the 40-60 cm horizon.

As it is not possible to install an access tube in the grid centered in the tree trunk, to estimate its water content, it was assumed that it was the same as in the one placed at 1 m from the trunk, in the direction of the row.

From the two differentiated areas (row, between rows), there was only one access tube installed between rows (as in NI and IRR), while all the others were in the row. As a consequence soil water content estimations were more accurate in the row (16 m^2) than between the rows (8 m^2).

As the access tubes were placed in a rectangular grid, it was assumed that each represented 1/9 of the total area in NI plots, and 1/25 in the IRR plots. This assumed that each access tube was replicated in symmetric positions with respect to the longitudinal and transverse axes of the row, to cover the four tree quadrants.

In the between rows area, the single installed access tube was considered to represent the whole area (8 m^2).

Drainage

Drainage was estimated from water content changes between 0.60 and 1.20 m. These limits were based on observations taken in trenches, which practically showed a total absence of roots below 0.60 m (García Petillo, 2002). Using the same grid of access tubes and the same methodology described above, determinations of soil water at 0.70 and 1.0 m depth were used for this horizon.

Kalma and Stanhill (1969), Castel and Buj (1993) and Domingo *et al*. (1996) also used trench observations to estimate the soil depth limit directly contributing to ETc.

In periods where there was an increase in water content in the deeper layer, it was assumed to be due to drainage from upper horizons.

Kalma and Stanhill (1969) estimated drainage in a similar way, but assumed that a decrease in water content below root depth was due to drainage losses to deeper horizons.

As stated previously, the capillary rise was considered negligible, as the freatic level was always at least 7 m deep.

Estimation of the crop coefficient Kc

The crop coefficient (Kc) was calculated using FAO methodology (Allen *et al*., 1998) as the ratio of crop evapotranspiration (ETc) and reference evapotranspiration (Kc = ETc/ETo). The ETc was estimated for each period using the water balance method as discussed above.

The ETo was calculated as:

$$ETo = Eo \times Kp$$

where Eo was the evaporation from a Class «A» pan, and Kp was the pan coefficient. The value of this coefficient depends on pan installation conditions. In this case, it was estimated for a pan surrounded by green cover up to a windward distance of 1000 m, and the mean relative humidity and wind speed for each month, using Allen *et al*. (1998) formulas.

Results

Water balance

The WB of the orchard was calculated for the period 27 May 1997 to 24 March 2000. The required measurements (total precipitation, precipitation with intensity less than 5 mm h^{-1}, soil water content and evaporation of Class «A» pan) were collected at approximately weekly periods. During the whole study period, 87 weekly periods with the above characteristics ($P_t < 30$ mm $week^{-1}$) were used.

The entire measurement period was 1,032 days, from which 728 days were used effectively. Of these 199 were in the winter, 202 in spring, 184 in summer, and 143 in autumn. To compare among seasons, values were normalized to an average period of 182 days $season^{-1}$ (Table 2).

Table 2. Water balance components. Average values for the 87 intervals indicated in the text, for the whole period of study (Total) and for each season, for non irrigated and irrigated trees, in the row, between rows and in the whole area

	P_t[1]	Run[2]	Int[3]	P_{ef}[4]	Irr[5]	ΔΘ[6]	Dra[7]	ETo[8]	ETc[9]
Non irrigated - 16 m^2 row									
Total	1,141	240	161	740	0	–655	126	3.14	1.74
Winter	346	93	31	221	0	–71	49	1.45	1.34
Spring	233	34	37	162	0	–279	17	4.06	2.33
Summer	279	48	48	182	0	–200	37	4.99	1.90
Autumn	281	65	46	171	0	–81	20	1.77	1.26
Non irrigated - 8 m^2 between rows									
Total	1,141	240	0	900	0	–484	211	3.14	1.61
Winter	346	93	0	252	0	–37	49	1.45	1.32
Spring	233	34	0	199	0	–256	48	4.06	2.23
Summer	279	48	0	230	0	–171	62	4.99	1.86
Autumn	281	65	0	216	0	17	51	1.77	0.81
Non irrigated - 24 m^2 whole area									
Total	1,141	240	107	793	0	–598	155	3.14	1.70
Winter	346	93	21	232	0	–60	49	1.45	1.33
Spring	233	34	25	175	0	–272	28	4.06	2.30
Summer	279	48	33	198	0	–190	45	4.99	1.88
Autumn	281	65	31	186	0	–48	31	1.77	1.12
Irrigated - 16 m^2 row									
Total	1,141	240	150	751	596	–462	152	3.14	2.28
Winter	346	93	28	224	0	–68	51	1.45	1.32
Spring	233	34	35	164	183	–201	28	4.06	2.86
Summer	279	48	45	185	343	–134	41	4.99	3.42
Autumn	281	65	43	173	57	–38	31	1.77	1.30
Irrigated - 8 m^2 between rows									
Total	1,141	240	0	900	0	–548	185	3.14	1.73
Winter	346	93	0	252	0	–42	59	1.45	1.29
Spring	233	34	0	199	0	–305	33	4.06	2.58
Summer	279	48	0	230	0	–176	39	4.99	2.02
Autumn	281	65	0	216	0	19	56	1.77	0.79
Irrigated - 24 m^2 whole area									
Total	1,141	240	100	801	397	–491	163	3.14	2.10
Winter	346	93	19	233	0	–59	54	1.45	1.31
Spring	233	34	23	176	123	–236	30	4.06	2.77
Summer	279	48	30	200	229	–148	40	4.99	2.95
Autumn	281	65	29	187	38	–19	39	1.77	1.13

[1] P_t: total precipitation. [2] Run: runoff. [3] Int: foliage interception. [4] Pef: effective precipitation. [5] Irr: applied irrigation. [6] ΔΘ: net variation of the volumetric soil water content in the 0-60 cm layer. [7] Dra: drainage. [8] ETo: reference evapotranspiration. [9] ETc: crop evapotranspiration. All values in mm, except the last two columns which are mm day^{-1}.

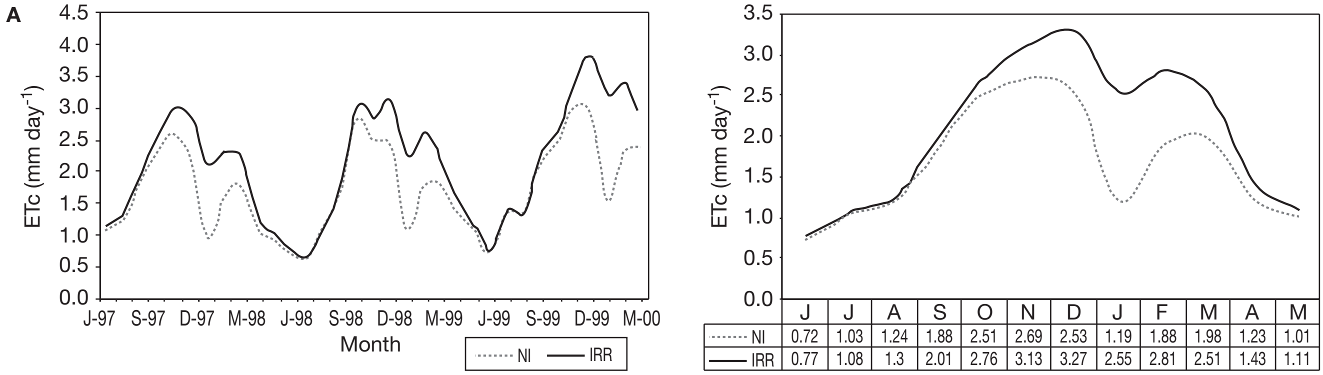


Figure 2. Monthly values of actual ETc, in non irrigated (NI) and irrigated (IRR) trees in the whole planting spacing. A: Changes during the whole study period of June 1997 to March 2000. B: Average monthly values for the same period. The standard deviations varied between 0.1 and 0.4 mm day^{-1} and the coefficient of variation between 10 and 25% for the different months.

Crop evapotranspiration

Monthly variation in ETc (Fig. 2A) shows a clear seasonal pattern, with a minimum in winter and maximum in spring/summer. The same pattern was observed in all the three seasons. Another constant is that the ETc was similar for both treatments in winter. Differences appeared as the season advanced, and reached a maximum difference in January. This difference increased from January 1998, to 1999, and again to 2000. Soil water content in NI was adequate in January 1998, low in 1999 and near permanent wilting point (PWP) in January 2000. This explains the increased differences in ETc between treatments.

Finally ETc changes during the three seasons shows that maximum annual peaks tended to increase from 97/98 to 99/00. They reached a maximum in December 1999 at 3.8 mm day^{-1}. This rise in ETc agrees with increased Eo with years.

The monthly average evapotranspiration (Fig. 2B) shows the same pattern discussed above. In January the ETc in the NI treatment decreased to less than half of that in the irrigated treatment. The average ETc in the month it reached a maximum (December), which is usually used as a design parameter for micro-irrigation systems, was 3.3 mm day^{-1} or approximately 80 L tree^{-1}day^{-1}.

Crop coefficient Kc

The Kc values were calculated in each period studied, and its mean and standard deviation were calculated for each month of the year. The number of periods used for each month was 7, 10, 7, 5, 5, 3, 4, 7, 3, 10, 10, and 7 from January to December, respectively. In spring and summer, the most important periods for irrigation management, there were more values available.

The values depicted in Figure 3 show that Kc was higher in the IRR than in the NI treatment in spring and summer when irrigation was being applied, and tend to be almost equal in autumn and winter to the NI treatment.

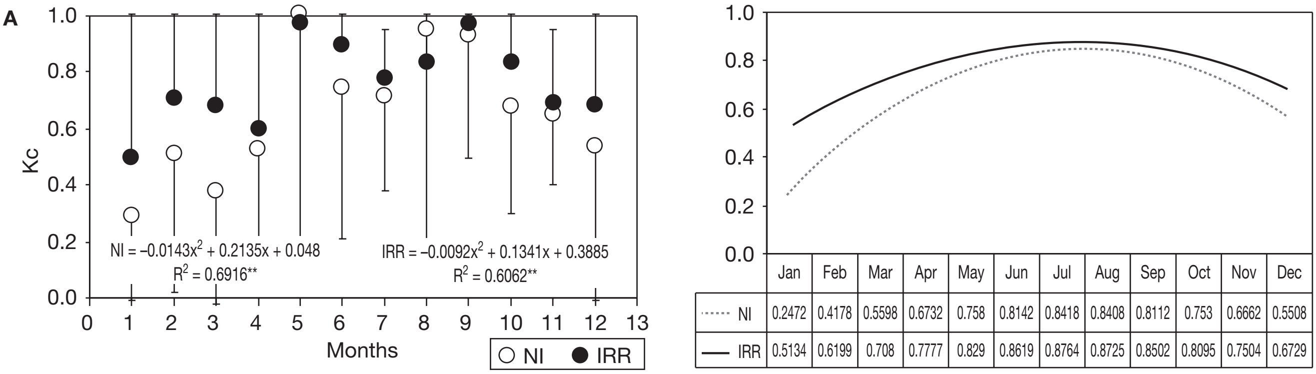
The average Kc over the whole period of the study referred to the plant spacing was 0.56 for the NI and 0.69 for IRR treatments. The extreme values of Kc were 0.88 in July (winter in the Southern Hemisphere), and 0.51 in January (summer in the Southern Hemisphere).

The results show a clear seasonal trend in both ETc and Kc, with minimum Kc values in summer (0.60), intermediate in autumn and spring (0.77 and 0.80, respectively) and maximum in winter (0.87). This trend was seen in all three seasons, in both treatments, both in the row and in-between the row areas.

Discussion

Water balance

Results for the non irrigated tree, on an annual basis, at the plant spacing used (Table 2) show that runoff was low (21% of total rainfall), compared to an average of about 35% calculated for the whole of Uruguay (Failache *et al.*, 2003). Direct interception by the tree canopy accounted to 9% of total rainfall. The relatively high (negative) value of $\Delta\Theta$ should be noted. These



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NI	0.2472	0.4178	0.5598	0.6732	0.758	0.8142	0.8418	0.8408	0.8112	0.753	0.6662	0.5508
IRR	0.5134	0.6199	0.708	0.7777	0.829	0.8619	0.8764	0.8725	0.8502	0.8095	0.7504	0.6729

Figure 3. A: Monthly values of Kc (ETc/ETo) without irrigation (NI) and with irrigation (IRR), for the whole planting area (24 m^2). Each value is the monthly mean ± SD calculated from several weekly intervals as explained in the text. Best fit equations as function of the month of the year, which were statistically significant (** $p<0.01$), are also included. B: Monthly values of Kc estimated from the equations in A.

three results are due to the same cause. The intervals selected were those when there was moderate or low rainfall and little runoff. Thus the intervals selected were biased towards periods of soil drying, while the disregarded periods were mainly at times of soil recharge. This also suggests that drainage may have been underestimated.

On an annual basis, drainage represented about 14% of total rainfall in NI plots and about 11% of total water (rainfall plus irrigation) in IRR plots. In both treatments values were higher between rows than within the rows (18 and 11% in NI, and 16 and 9% in IRR, respectively).

The similar values, on a whole area basis in both treatments (155 and 163 mm per year) is surprising. However, Fares and Alva (1999), in a sandy soil in Florida irrigated by micro-sprinkling, determined that 82% of total drainage was from rain, and only 18% from irrigation. Nonetheless their drainage values were substantially higher than those in this work, and were 47% of the total water (rain plus irrigation). The reason for this big difference is not clear, although they did work on sandy soils with a lower water holding capacity than the soil in this experiment. On the other hand, Andreu *et al*. (1997) found that almost all water loss due to drainage occurred under the drippers, due to excessive irrigation.

In the row, losses were greater in IRR plots than in NI plots (152 and 126 mm, respectively). This was presumably due in irrigated trees where was less pore space available in the soil. In winter, when there is no irrigation, the losses were similar in both treatments.

On the contrary, between rows, losses were higher in NI plots than in IRR plots (18 and 16%, respectively). Presumably this difference was due to the observed greater vegetative development of grass cover between rows in IRR plots.

The average ETc for the whole experimental period for the whole area was 24% higher in IRR plots than in NI plots (2.1 and 1.7 mm day^{-1}, equivalent to 767 and 620 mm $year^{-1}$, respectively).

The seasonal trend showed that in winter and autumn (when there was no irrigation) ETc values were almost identical in both treatments (1.33 and 1.31 mm day^{-1} in winter, and 1.12 and 1.13 mm day^{-1} in autumn for IRR and NI plots, respectively). This coincidence in WB, for both treatments, suggest high confidence in the methodology used.

During irrigation periods, as expected, the ETc was higher in IRR than in NI plots in spring (2.77 and 2.30 mm day^{-1}) and the difference even larger in summer (2.95 and 1.89 mm day^{-1} respectively). The ETc in NI plots in summer was lower than in spring, both between and in rows, even though atmospheric demand was higher in summer. The results suggest that ETc was limited due to water stress in NI plots in summer, as shown by the lower soil water content and the reduced growth of grass cover in the NI treatment.

Following Allen *et al.* (1998), we considered that direct evaporation from the soil fraction wetted by drippers in the IRR was negligible. The area was all shaded by vegetation and thus not exposed to radiation. Direct evaporation from between rows following rain was taken as the same in both treatments.

Analyzing each area separately, the between row ETc in the IRR plots was slightly higher than in the NI plots (1.73 and 1.61 mm day^{-1} respectively). This difference became greater in spring and summer. Presumably this was due to increased growth of the grass cover in IRR plots, as suggested above.

In the row area, differences between treatments were, as expected, greater. On average, over the whole period the ETc in IRR plots was 31% greater than in NI plots (2.28 and 1.74 mm day^{-1}). During winter and autumn there were almost no differences between treatments but in spring the difference increased to 23% (2.86 and 2.33 mm day^{-1}) and in summer it went to 80% (3.42 and 1.90 mm day^{-1}). The fact that the highest ETc differences between treatments were in the row, and during the spring/summer period (i.e. just where and when irrigation was applied) confirms that it was the cause of the differences.

Crop evapotranspiration

During the three seasons the ETc in NI plots decreased remarkably in January (summer in Southern Hemisphere) with respect to December and February, even though atmospheric demand was not decreased (Fig. 2). It is certain that the soil water content was not sufficient to satisfy the demand. However, irrigated trees (IRR treatment) also had a reduced ETc in January. In each year, maximum ETc was reached in December, it decreased in January, and increased again in February. This suggests the involvement of stomatal regulation mechanisms in response to atmospheric condition (e.g. vapour pressure deficit, VPD), even with full irrigation. However, stomatal conductance was not measured to confirm this hypothesis.

It is difficult to compare these results with other published work, mainly due to the different experimental methods used. The precision that can be obtained using the WB method is lower than that which can be obtained using a weighting lysimeter. Even for papers that used the WB method, the accuracy of the estimates depends on several factors, such as the method of measuring or estimating drainage, the density of sites used to measure soil water content, or the frequency of measurement (daily, weekly, monthly). These should be considered in the analysis of the following information.

With these considerations in mind we have collected the results of different authors (Table 3). In some cases these have been normalized to bring them to the same base; i.e., the whole plant spacing, and the seasonal or annual average.

The Table 3 results show two regions differentiated by their ETc. A «moderate» region that includes Florida, Valencia, the less arid area of Israel and Uruguay, with winter values of less than 2 mm day^{-1}, in summer between 3 and 4 mm day^{-1}, and an annual average between 1.9 and 2.4 mm day^{-1}. The other region, which is «more extreme», includes Texas, Arizona, South Africa, and Iran, and is characterized by an annual average ETc greater than 3 to 4 mm day^{-1}, with extreme summer values of 5 to 8 mm day^{-1}.

Some of the above dispersion in values may be due to differences in the method of determination used, as mentioned earlier, However, two experiments that used weighting lysimeters (Du Plessis, 1985; Castel, 2000), which are considered to be the most accurate method of determining ETc (Aboukhaled *et al.,* 1982), gave the most contrasting results. Du Plessis (1985) used mature 'Valencia' orange trees, and Castel (2000) young 'Clementines' that did not cover the whole planting

Table 3. Annual and seasonal average ETc values (mm day^{-1}) of mature citrus trees, in different citrus growing areas

Reference	Region	Winter	Spring	Summer	Autumn	Year
Koo and Sites (1955)[1]	Florida, USA	1.7	2.7	4.0	2.8	2.8
Kalma and Stanhill (1969)	Israel	1.1		4.4		2.3
Hoffman *et al.* (1982)	Arizona, USA	1.1	4.0	7.3	3.7	4.0
Smajstrla *et al.* (1982)[1]	Florida, USA	1.9		3.9		
Wiegand and Swanson (1982)	Texas, USA	1.8	2.6	4.8	3.7	3.2
Du Plessis (1985)[1]	South Africa	2.3		6.0-8.5		
Castel *et al.* (1987)	Valencia, Spain	0.9-1.0	1.5-2.0	3.0-3.2	1.4-1.8	1.7-2.0
Sepaskhah and Kashefipour (1995)	Iran	1.4	4.4	8.5	4.2	4.6
Fares and Alva (1999)	Florida, USA	<1.0		>4.0		
Castel (2000)	Valencia, Spain	0.7-1.0		2.0-2.8		1.9
This paper	Uruguay	1.3	2.8	3.0	1.1	2.1

[1] Values elaborated for ease of comparison.

area, a doubled ETc must have been the result of extreme climatic differences.

Crop coefficient Kc

As in this work, a higher Kc in well irrigated trees compared to restricted irrigation, has been reported by Castel and Buj (1990, 1993), Sepaskhah and Kashefipour (1995) and Chartzoulakis *et al*. (1999).

Fares and Alva (1999) indicated that variation in daily ETc values, even in short intervals, in the same month, could be due to water availability to the trees and/or climatic conditions. Castel (2000), in agreement with Annandale and Stockle (1994), showed a non constant Kc over the whole season, and that Kc values were not independent of climatic conditions. Castel (2000) found that monthly Kc in each year was highly correlated with solar radiation, but was less correlated with wind speed, vapour pressure deficit, or temperature. Kalma and Stanhill (1969) also found that seasonal fluctuation in ETc did not have a clear or smooth trend over time.

Allen *et al*. (1998), for arid or semiarid regions of Mediterranean type and for trees of comparable size to those in this experiment, recommended Kc values from 0.70 in winter to 0.65 in summer, with no ground cover. With growing ground cover or weeds values range from 0.75 to 0.70, respectively. For humid or sub-humid climates, it is suggested that these values should be increased by 0.1 or 0.2.

The average yearly Kc value of 0.69 is in good agreement with reports from Israel (Kalma and Stanhill, 1969), Arizona (Hoffman *et al.*, 1982), Valencia (Castel and Buj, 1993), Cyprus (Eliades, 1994), Iran (Sepaskhah and Kashefipour, 1995), Crete (Chartzoulakis *et al.*, 1999) and California (Grismer, 2000).

However, there were exceptions. Wiegand and Swanson (1982) in Texas, reported a Kc value of 0.89. The trees they used were very large, mainly at the end of the period, (more than 80% ground cover for trees spaced at 6.70 × 4.60 m) compared with our trees (50% ground cover, spaced at 6.00 × 4.00 m).

In Italy, Dettori and Filigheddu (1994) reported a Kc value of 0.39. They stated that their low ETc values were due to the use of young tress. However, their trees were 10 years old, 3 m high and covered 42% of the frame, which is similar to our 'Valencias' in Uruguay.

With regard to trends in Kc there are contradictory results from other authors. Some reported maximum Kc in summer. Durán (1993) with information for the North of Uruguay; Hoffman *et al*. (1982), for mature 'Valencia' orange trees in Arizona; Sepaskhah and Kashefipour (1995) for mature sweet lime trees in Iran and Chartzoulakis *et al*. (1999) for mature orange trees in Crete, estimated an increased Kc from spring to summer, and a decrease after that until the autumn.

Other workers have observed the same trend as in this study. Wiegand and Swanson (1982) for mature 'Valencia' orange trees in Texas; Castel (2000) for 'Clementines' in Valencia using a weighting lysimeter over nine years; Grismer (2000) for mature lemon trees in California and Kalma and Stanhill (1969) for mature 'Shamouti' orange trees in Israel, found Kc was at a maximum in winter and a minimum in summer.

A possible explanation to this can be obtained from Kauffman (1977). Transpiration from citrus seedlings growing in humid and in dry air was determined. In the second case evaporative demand was 2.5 times greater. However, ETc rates were almost the same in both environments, caused by the low air humidity which induced partial stomatal closure. That meant that as evaporative demand increased, ETc did not increase at the same rate, due to the plants' regulation mechanisms. Kahiri and Hall (1976) and Camacho-B (1977), came to the same conclusion. As a result, Kc in summer should be lower than in winter.

Ginestar (1995) had similar results with 'Clementina de Nules' in Valencia. She found higher Kc values in autumn and winter. This correspond with months with lower evaporative demand and higher relative humidity, suggesting that the stomata were more open in humid air. Green and Moreshet (1979) also reported higher Kc values when evaporative demand was low than when it was high.

However, at the orchard level, with mature trees, ETc is not only regulated by the stomatal reaction to the VPD, but also by the aerodynamic canopy resistance (Kalma and Fuchs, 1976; Daamen *et al*., 1999).

In conclusion, actual evapotranspiration for a mature, drip irrigated, citrus orchard in the South of Uruguay, was 767 mm $year^{-1}$. Average evapotranspiration during the month of maximum demand was 3.3 mm day^{-1}, approximately 80 L $tree^{-1}$ day^{-1} (on a plant spacing of 24 m^2). This value should be used as the base for the design of micro-irrigation systems, for mature citrus trees in Uruguay. The average crop coefficient (Kc) for the whole study period and for the whole plant spacing was 0.69. There was clear seasonal behaviour. There were minimum Kc values in summer

(0.60), intermediate values in autumn and spring (0.77 and 0.80, respectively) and a maximum in winter (0.87). Despite the fact that there was no treatment replication in space, this seasonal trend was observed in all of the three years of evaluation. Actual evapotraspiration decreased in January, the month with high ETo, even under full irrigation.

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