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Seasonal variations in sap flow and soil evaporation in an olive (*Olea europaea* L.) grove under two irrigation regimes in an arid region of Argentina

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ABSTRACT

The emergence of intensively managed olive plantations in arid, northwestern Argentina requires the efficient use of irrigation water. We evaluated whole tree daily transpiration and soil evaporation throughout the year to better understand the relative importance of these water use components and to calculate actual crop coefficient (Kc) values. Plots in a 7-year-old 'Manzanilla fina' olive grove with 23% canopy cover were either moderately (MI) or highly irrigated (HI) using the FAO method where potential evapotranspiration over grass is multiplied by a given Kc and a coefficient of reduction (Kr). The Kc values employed for the MI and HI treatments were 0.5 and 1.1, respectively, and the Kr was 0.46. Transpiration was estimated by measuring main trunk sap flow using the heat balance method for three trees per treatment. Soil evaporation was measured using six microlysimeters in one plot per treatment. Both parameters were evaluated for 7–10 consecutive days in the fall, winter, mid-spring, summer, and early fall of 2006–2007. Maximum soil evaporation was observed in the summer when maximum demand was combined with maximum surface wetted by the drips and evaporation from the inter-row occurred due to rainfall. Similarly, maximum daily transpiration was observed in mid-spring and summer. Transpiration of MI trees was 30% lower than in HI trees during the summer period. However, this difference in transpiration disappeared when values were adjusted for total leaf area per tree because leaf area was 28% less in the MI trees. Transpiration represented about 70–80% of total crop evapotranspiration (ETc) except when soil evaporation increased due to rainfall events or over-irrigation occurred. We found that daily transpiration per unit leaf area had a positive linear relationship with daily potential evapotranspiration ($r^2 = 0.84$) when considering both treatments together. But, a strong relationship was also observed between transpiration per unit leaf area and mean air temperature ($r^2 = 0.93$). Thus, it is possible to predict optimum irrigation requirements for olive groves if tree leaf area and temperature are known. Calculated crop coefficients during the growing season based on the transpiration and soil evaporation values were about 0.65–0.70 and 0.85–0.90 for the MI and HI treatments, respectively.

1. Introduction

Arid lands dedicated to olive production have increased dramatically during the last 15–20 years in Argentina (i.e., an increase of 30,000–90,000 ha) with the country emerging as the largest producer outside of the Mediterranean Basin and Middle East (http://www.alimentosargentinos.gov.ar/olivicola). Much of this production is oriented towards the exportation of table olives (80,000 tons in 2007) although olive oil production is gaining prominence. Most of the new plantations are located in northwest Argentina, a subtropical arid region near the Andes Mountains with climatic characteristics different from those of the Mediterranean. Precipitation (100–400 mm annually) occurs primarily in the summer as brief, torrential downpours and winter temperatures are relatively mild compared to the Mediterranean in most years (Ayerza and Sibbett, 2001). Under these climatic conditions, orchards are often irrigated 10–12 months per year using micro-irrigation systems (Rousseaux et al., 2008), and the irrigation water is mostly obtained from subsurface aquifers (100–200 m below the surface).

Although definitive studies have not yet been conducted, yearly extraction of water by the agricultural sector is likely greater than recharge considering the high annual potential evapotranspiration values (ETo; 1550–1700 mm) over grass as a reference using the Penman–Monteith equation (Allen et al., 1998), and low rainfall in the region. Additionally, global change models predict a reduction

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in precipitation in the Andes region of northwestern Argentina over the coming years which may exacerbate potential difficulties (Minetti et al., 2003; Dore, 2005). Under this scenario, the rational use of irrigation water in olive plantations is crucial for the sustainability of the production system.

In most of the orchards of this region, irrigation rate is calculated using the FAO method (i.e., irrigation = ETo × Kc × Kr) by multiplying the daily ETo estimated from automatic weather station data by a crop coefficient (Kc) and a reduction coefficient (Kr) associated with the percentage of ground covered by the tree canopies (Fereres and Castel, 1981). Most of the weather stations in these orchards are located over bare soil, which represents a value of ETo 10–15% higher than ETo over reference grass conditions and may lead to an over-estimation of irrigation levels. Crop coefficient values of around 0.6–0.8 are typically employed to satisfy crop demand based on results from California (Goldhamer et al., 1993; Grattan et al., 2006) and Spain (Girona et al., 2002; Moriana et al., 2003). However, higher Kc values (up to 1.0) are occasionally used due to low water costs and minimal regulation of the industry.

The studies mentioned above have empirically determined Kc by evaluating the fraction of ETo applied as irrigation water needed to maximize yield. In this context, the extrapolation of Kc from Mediterranean climate conditions to the northwest of Argentina could introduce deviations in optimal irrigation scheduling. Additionally, in the last several years, there has been substantial effort to quantify and model the different components of water use in woody perennial crops with the aim of obtaining less time consuming estimates of Kc along with more accurate estimations of water use (i.e., Yunusa et al., 2004; Testi et al., 2006a; Alves et al., 2007). The components of water use can be estimated by several methods in tree crops. For example, Alves et al. (2007) used lysimeters with and without the presence of lime trees to quantify transpiration and evaporation from leaves and soil. Orgaz et al. (2007) estimated transpiration of olive trees using a water balance procedure based on monitoring changes in soil water content in a system in which soil evaporation was prevented. Another approach is the more direct measurement of plant transpiration using sap flow meters (e.g., Fernández et al., 2001, 2008; Dragoni et al., 2005; Pereira et al., 2006) and soil evaporation using microlysimeters (e.g., Bonachela et al., 1999). Last, the measurement of water vapor fluxes from orchards with the eddy covariance technique has been used for assessing evapotranspiration (Villalobos et al., 2000; Testi et al., 2004; Williams et al., 2004).

For the determination of olive water requirements, Testi et al. (2006a) proposed a model capable of separately calculating transpiration, intercepted rainfall evaporation, and soil evaporation. Using this approach, transpiration is calculated using the olive-specific model proposed by Orgaz et al. (2007) which uses the calculated canopy-intercepted photosynthetically active radiation (PAR) and measured average daytime temperature as the two driving variables for estimating canopy conductance. At our experimental site, where precipitation is only about 100 mm annually, evaporation from leaf surfaces is of relatively minor consequence and soil evaporation is often limited to the area wetted by the drip emitters. Thus, tree transpiration should represent the majority of orchard water use and its quantification is critical for accurate irrigation scheduling. In addition to Orgaz et al. (2007), other authors have recently proposed similar model approaches for estimating transpiration in olive under Mediterranean conditions (Yunusa et al., 2008; Fernández et al., 2008). If calculated transpiration values from such models agree well with transpiration values deduced from sap flow measurements under subtropical arid climate conditions, olive orchard water management could be greatly improved in our region.

The objectives of this study were to: (1) determine the evaporation and transpiration components of water use in an olive orchard in northwest Argentina (La Rioja) for several periods during the course of the year under two different irrigation regimes, (2) calculate actual Kc values for these same periods based on the measured water use components, (3) relate daily sap flow to meteorological variables such as temperature and ETo, and (4) compare calculated transpiration values from the Orgaz et al. (2007) model with those obtained from sap flow measurements.

2. Materials and methods

2.1. Experimental site and irrigation treatments

An irrigation experiment was conducted from September 6, 2005 to May 22, 2007 using 7-year-old olive trees (*Olea europaea* L. cv. 'Manzanilla fina') in a commercial orchard with a loamy sand soil texture located 15 km east of Aimogasta in the province of La Rioja, Argentina (28°33′S, 66°49′W; 800 m above sea level). Tree spacing was 4 m × 8 m with a north-south row orientation and canopy cover was 23% with 3.5–4.0 m tree height. Irrigation was supplied by eight drip emitters per tree using two drip lines. The drip lines were spaced approximately 1 m apart (i.e., 0.5 m on each side of the tree trunk), and the emitters were installed continuously at 1-m distances along the drip lines. The emitters had a discharge rate of either 2 or 4 $\mathrm{l\,h^{-1}}$ depending on the particular treatment imposed.

The standard FAO formula for crop evapotranspiration (ETc = ETo × Kc × Kr) was used for calculating the irrigation amounts where ETo is potential evapotranspiration over grass as a reference, Kc is the crop coefficient (Allen et al., 1998), and Kr is the coefficient of reduction associated with percentage crop cover (Fereres and Castel, 1981). The two treatments were a highly irrigated (HI) treatment with a Kc of 1.1 and a moderately irrigated (MI) treatment with a Kc of 0.5. The experimental trees had a Kr of 0.46 based on measurements of tree canopy diameter and subsequent calculations of the percentage of ground area covered by the canopies (23%). Treatments were maintained from the beginning of September to the end of May each season with 2–3 weekly irrigation events. The trees in the experimental plots had not been used previously for experimental purposes, and had a similar irrigation history. During the winter of 2006 (i.e., June–August), both treatments were irrigated approximately every 2 weeks with a Kc = 0.4 to avoid excessive irrigation (Rousseaux et al., 2008). Meteorological data were collected from an automated weather station (Davis Instruments, Hayward, CA, USA) located in a large cleared area with bare soil within the commercial orchard, and were used to calculate daily ETo values with the Penman–Monteith equation. These values were adjusted for reference conditions over grass using Annex 6 of Allen et al. (1998) and utilized in the irrigation scheduling in this study. However, both ETo values over bare soil and over grass are presented in Section 3. All plots were irrigated with a total of 45 mm in the winter of 2006 (June–August), while the MI treatment received 400 mm and the HI treatment received 900 mm from spring 2006 to fall 2007 (September–May). Irrigation amounts were somewhat less in 2005–2006 due to smaller tree size.

2.2. Sap flow measurements

The experimental design for the sap flow measurements was a completely randomized block design ($n = 3$), and each block contained one plot of each treatment with a plot consisting of six adjacent trees within a tree row. Measurements were performed on one central tree within each plot (i.e., $n = 3$ measured trees per irrigation treatment) during five periods of 7–10 days each in 2006–2007: fall (May 12–20), winter (August 1–10), mid-spring (November 8–15), summer (January 17–24), and early fall (March 21–28). Sap flow of main trunks was measured using the heat balance method (Flow 32, Dynamax Inc., TX, USA). Sensors (model SGA150) were installed on trees with trunk diameters ranging from 12.5 to 14.5 cm. The trunks were cleaned prior to installation but were not otherwise modified. The amount of silicone applied to the sensor and the amount of canola oil applied to the bark were reduced to a minimum following the recommendations of Grime and Sinclair (1999). Because a preliminary field test in January 2006 showed that olive bark may be sensible to heating (i.e., cracking) over extended periods, we only conducted measurements for 7–10 consecutive days. Power supply was adjusted daily by changing the heater input (5 W or less were used) to keep the heating (dT) of the trunk between 0.3 and 8 °C. The sensors were heavily insulated as was the soil surface (20 cm diameter around the trunk) to reduce undesired heat fluxes. Measurements with unheated sensors for 3 days before each measurement period indicated that potential undesired heat fluxes were small and no corrections were employed. The sensors were connected to a Campbell CR10X data logger (Campbell Scientific, Logan, UT, USA) with readings taken every 60 s and averaged over 15 min. Plant transpiration was calculated as the daily accumulation of sap flow values.

2.3. Soil evaporation

Soil evaporation measurements were performed in one block (i.e., one plot per irrigation treatment) using six microlysimeters per plot (Fig. 1). Each plot was divided into the tree zone (about 25% of the total area) and inter-row spacing (75%). The area allocated to individual trees within a row was 8.8 m^2 based on the width of the rooting systems (approximately 1.1 m on each side of the tree trunk) and the distance between the tree trunks (4.0 m). Rooting system width was utilized because it represents the soil surface where plant water uptake directly affects evaporation. The soil surface consisted of both wet and dry surface areas due to the drip irrigation in combination with sun-lit and shaded areas (i.e., wet + shade, wet + sun, dry + shade, dry + sun). Four ML were placed in the tree zone to assess soil evaporation for these various microclimatic conditions. Another ML was located between the two drip lines and equidistant from the adjacent tree canopies in the driest area of the tree zone. Last, one ML was installed 4 m from the tree row in the inter-row spacing. Overall soil evaporation was calculated by multiplying the evaporation from each ML by the fraction of the area that each ML represented (Bonachela et al., 2001).

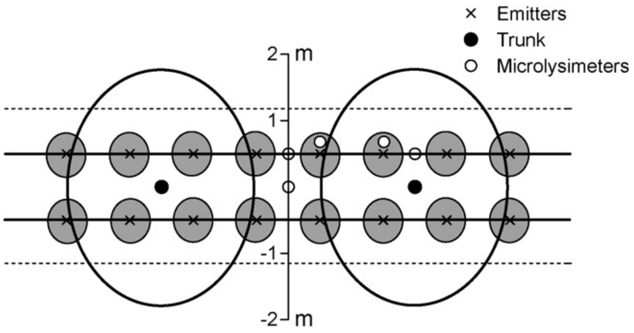

Fig. 1. Position of the soil evaporation microlysimeters relative to the tree canopy and drip emitters. The diameter shown for the soil surface wetted by individual drip emitters (0.58 m) was representative of the moderately irrigated treatment. The average diameter for the highly irrigated treatment was 0.78 m. An additional microlysimeter was located 4.0 m from the tree row in the center of the inter-row spacing (position not shown). The dashed lines indicate the approximate width of the rooting zone.

The ML used in this study were made of PVC tubing (6 cm diameter × 15 cm length) and similar in design to those of Bonachela et al. (1999). The soil cores used in the experimental plots were extracted from predefined areas outside of the plots that corresponded with the various microclimatic conditions mentioned above. After sealing the bottom of the ML with a plastic cap and weighing the ML, they were installed in the desired locations 1 day after irrigation. The ML were enveloped with a thin plastic sheet to minimize the gap between the ML casing and the surrounding soil. Because irrigation was conducted every 2–3 days, the ML could only be weighed for 1 or 2 days to assess water mass loss and calculate soil evaporation. Mass measurements were performed between 07:30 and 09:30 h solar time using an electronic scale (model OAC-24, Moretti, Buenos Aires) with a resolution of 1 g.

2.4. Leaf area density and total leaf area per plant

Leaf area density (LAD; m^2 leaf area per m^3 of canopy volume) was estimated for each of the six experimental plants using a leaf count method similar to Villalobos et al. (1995) in which the number of leaves contained in a known cubic volume (20 cm × 20 cm × 20 cm) were counted at various positions in the canopy and multiplied by the average individual leaf area. Leaves were counted within the cube along five horizontal radii (North, South, Southeast, East, West) centered at the trunk at breast height and along one vertical radius from the midpoint of tree height to the top of the canopy. Distances of 0–25, 25–50, 50–75, 75–125, and 125–175 cm from the trunk or vertically from the midpoint were used. Average individual leaf area was determined by sampling five leaves at five points within the canopy of each tree per irrigation treatment for a total of 90 leaves per treatment. Discs were then punched from these leaves and used to calculate the specific leaf mass (g cm^{-2}) and area per leaf after the material was dried at 60 °C for 72 h. Determinations of LAD were performed in September 2006 (before vegetative growth started), January 2007, and March 2007. Total tree leaf area was calculated as LAD × canopy volume. Leaf area was also assessed in one of the three experimental blocks (i.e., two trees) using a portable plant canopy analyzer (LiCor-2000, Lincoln, NE, USA), and values from the two methods were within ±10%.

2.5. Calculation of experimental crop coefficients

The calculated crop coefficients of the various measurement periods for the HI and MI treatments were determined by summing the coefficients of plant transpiration (Kp), soil evaporation from the tree zone (Ks1), and soil evaporation from the inter-row (Ks2). These individual components of Kc were determined using the standard FAO formula (ETc = Kc × Kr × ETo) with ETc being substituted by either the average value of canopy transpiration or soil evaporation for a given measurement period. The coefficients were normalized to approximate Kc values for a mature olive orchard by converting the canopy transpiration values from our 23% canopy cover (Kr = 0.46) to 50–60% canopy cover (Kr = 1) in order to facilitate comparisons with other studies. The Kc values were calculated using ETo over bare soil to best reflect the desert conditions in our region and lack of weather stations under reference (grass) conditions.

2.6. Model values of daily transpiration

We compared our measured values of daily transpiration from each tree estimated from sap flow against transpiration values obtained using the Orgaz et al. (2007) model of bulk daily canopy conductance (g_c). The model is based on the Penman–Monteith 'big

Table 1
Daily averages of maximum temperature (°C), minimum temperature (°C), maximum relative humidity (%), minimum relative humidity (%), solar radiation (MJ m^{-2} d^{-1}), wind speed (m s^{-1}), potential evapotranspiration over bare soil (mm d^{-1}), and estimated potential evapotranspiration for reference conditions (i.e., over grass). Data are the averages for the dates in which sap flow and soil evaporation were measured during the 2006–2007 season.

Dates	Temperature		Relative humidity		Solar radiation (MJ m^{-2} d^{-1})	Wind speed (m s^{-1})	ETo over bare soil (mm d^{-1})	ETo reference (mm d^{-1})
	Maximum (°C)	Minimum (°C)	Maximum (%)	Minimum (%)				
May 12–20, 2006	22.4	7.3	73.1	29.3	14.1	2.3	3.2	2.8
August 1–10, 2006	19.0	3.3	72.2	27.3	16.0	2.4	3.2	2.9
November 8–15, 2006	33.9	19.0	45.0	17.5	29.5	3.0	8.4	6.6
January 17–24, 2007	34.4	20.7	73.3	24.5	29.5	3.2	8.3	7.1
March 21–28, 2007	27.6	17.2	81.1	43.0	19.1	3.7	5.0	4.6

leaf' equation, and daily mean canopy conductance (mm s^{-1}) is calculated as:

$$g_c = \frac{\gamma}{\rho C_p}\frac{QR_{sp}}{D}f(T_d) \qquad (1)$$

where $f(T_d)$ is a function of mean daytime temperature (°C), R_{sp} is the mean PAR irradiance (MJ m^{-2} d^{-1}), D is the mean daily vapor pressure deficit (VPD, kPa), ρ is the density of air (kg m^{-3}), C_p is the specific heat of air at constant pressure (kJ kg^{-1}), γ is the psycrometric constant (kPa K^{-1}), and Q is the fraction of PAR intercepted by the canopy using a subroutine of the Orgaz et al. (2007) model. Transpiration (E_p) is then calculated based on the formula of McNaughton and Jarvis (1983):

$$\lambda E_p = \frac{\rho C_p D}{\gamma} g_c \qquad (2)$$

Essentially, g_c and transpiration are determined by inputting standard weather station into the model and by estimating the fraction of PAR intercepted by the canopy (Q) based on planting density, tree canopy volume per unit surface, and LAD. We used the LAD values measured at our experimental orchard rather than the modeled values because our tree canopy LAD values exceeded the defined domain (1.2–2.0 m^2 m^{-3}) of the model. Mean daily temperature (i.e., a 24-h mean) was also used rather than the mean daytime temperature (i.e., during daylight hours) because it provided a 10% better fit between the calculated and observed daily transpiration values. This better fit using the 24-h temperature mean may have occurred because some sap flow was observed 3–4 h after sunset, or it is possible that another parameter was overestimated. No other adjustments were made to the model. Measurements of PAR transmitted by the canopy using a 1 m long, integrated light bar (Cavadevices, Buenos Aires, Argentina) were taken on several occasions and were in good agreement with the modeled values.

2.7. Statistical analysis

Mean comparisons between the MI and HI treatments of sap flow, LAD, tree volume, and leaf area per tree were performed for each measurement period using a one-way analysis of variance for a completely randomized block design ($n = 3$) (Statistical Analysis Software, Cary, NC, USA). Relationships between sap flow and climatic variables were fitted using GraphPad Prism software (San Diego, CA, USA) or TBL curve (Jandel Scientific, Corte Madera, CA, USA). Because the microlysimeters were only located in one plot per MI and HI treatment, soil evaporation within the tree zone was evaluated for each measurement period using each day as a replicate to allow for some statistical comparison.

3. Results

Average maximum and minimum daily temperatures were 19.0 and 3.3 °C during the August measurement period (i.e., winter), while maximum and minimum daily temperature values were 34.4 and 20.7 °C during the January measurements (i.e., summer; Table 1). During the spring November measurements, an unusually warm, dry air mass was present with average maximum temperature and minimum relative humidity of 33.9 °C and 17.5%. Maximum relative humidity during this same period was 45.0%. Potential evapotranspiration over bare soil (i.e., conditions typical of this desert region) was approx. 3 mm d^{-1} in May (i.e., fall) and August and over 8 mm d^{-1} in November and January. Estimations of ETo for reference conditions (grass) are shown as well in Table 1.

Average daily values of canopy transpiration estimated from sap flow were at their maximum during the warm spring period (November; 2.0 mm d^{-1}) and at their minimum during the winter (August; 0.23 mm d^{-1}) (Fig. 2A). Transpiration in the HI treatment was 31% higher than in the MI treatment in the summer (January; $P = 0.10$). There was also some tendency for trees in the HI treatment to have higher transpiration rates in November and March (early fall), but no significant differences were observed likely because the trees had already adjusted to the MI treatment

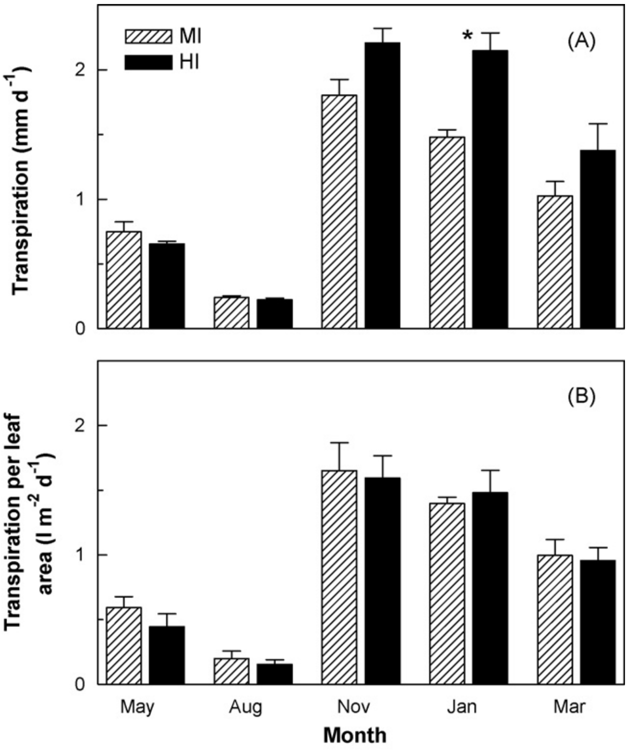

Fig. 2. Average daily values of canopy transpiration (A) and canopy transpiration relativized for leaf area (B) for the moderately (MI) and highly (HI) irrigated treatments during the 2006–2007 season. Averages are $n = 3$ trees per irrigation treatment. *$P < 0.10$.

Table 2
Leaf area density (LAD; $m^2\ m^{-3}$), tree volume (m^3), and leaf area per tree (m^2 tree $^{-1}$) for the moderately (MI) and highly irrigated (HI) treatments from September 2006 (early spring). $n = 3$ Replicates per irrigation level with means ± standard error.

Irrigation treatment	LAD ($m^2\ m^{-3}$)	Tree volume (m^3)	Leaf area per tree (m^2 tree^{-1})
MI	2.34 ± 0.10**	15.3 ± 1.6	35.8 ± 3.9
HI	2.94 ± 0.13**	16.9 ± 1.8	49.9 ± 7.2

** Significant differences between irrigation treatments at $P < 0.05$.

by reducing vegetative growth (data not shown) and possibly increasing leaf senescence. Along these lines, leaf area density of the MI trees was 20% lower than for the HI trees ($P < 0.05$; Table 2). Additionally, total leaf area per tree was also 28% lower in the MI trees although the difference was not significant due to variability in the initial tree size. When daily transpiration values were adjusted for the leaf area of each individual tree, the percentage differences between treatments over the entire experiment were reduced from approx. 20% to less than 5% (Fig. 2B).

Soil evaporation from the tree zone (Es1) was greater in the HI than in the MI plot in November (0.83 vs. 0.51 mm d^{-1}) and in March (0.61 vs. 0.32 mm d^{-1}) ($P < 0.05$; Fig. 3). These differences were largely related to the greater surface area wetted by the drip emitters in the HI treatment. No differences in Es1 were apparent between treatments in January due to three rainfall events that occurred shortly before the start of this experimental period (i.e., 34 mm in total). Values of Es1 were similar between irrigation treatments in May (fall) and August. Evaporation from the inter-row area (Es2) only occurred during the colder May (0.27 mm d^{-1}) and August (0.11 mm d^{-1}) periods and in January (0.71 mm d^{-1}) due to the rainfall.

The calculated plant coefficients (Kp) during much of the growing season ranged from 0.45 to 0.60 and 0.40 to 0.50 for the HI and MI treatments, respectively (Fig. 4), when calculated using ETo over bare soil as is typical of the region. Only during August (Kp = 0.15) when daily average temperatures were below 13 °C were lower values apparent. Values of Ks1 were about 0.20 in the HI treatment and were approx. 20% lower on average in the MI treatment due to the smaller area wetted by the emitters. In January, similar Ks1 and Ks2 values occurred in both treatments due to the rainfall events mentioned earlier. Values of Ks1 and Ks2 were high during May in both treatments due to over-irrigation. This occurred because ETo decreased rapidly during the fall and irrigation amounts were adjusted only every 15 days.

Typical values of calculated Kc excluding the effects of rainfall (i.e., Kp + Ks1) for the spring, summer, and early fall were 0.7–0.8 under HI conditions when calculated using ETo over bare soil with about 73% of Kc being tree transpiration and 27% as soil evaporation. Values for the MI treatment were about 0.55–0.6 with transpiration representing a somewhat greater percentage (78%) of water use than in the MI treatment. It is likely that the fairly high transpiration values in the MI treatment during November (i.e., spring) and January (i.e., summer) were sustained by using water stored in the deeper soil depths (Correa-Tedesco, unpublished data). Rainfall in January may have had some influence although soil water content was higher in the HI than the MI treatment. Comparison with Kc values estimated using reference (grass) ETo conditions is given in Section 4.

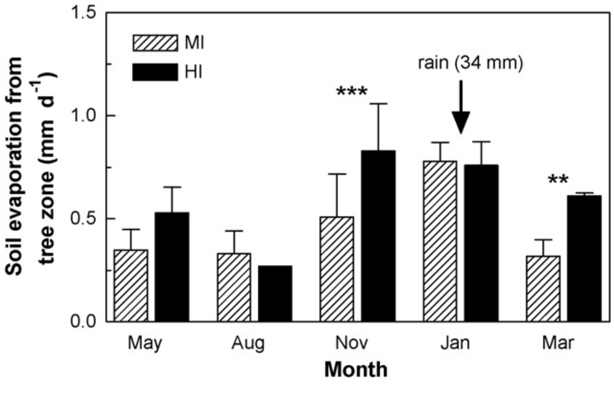

Fig. 3. Average daily values of soil evaporation from the tree zone for the moderately (MI) and highly irrigated (HI) treatments during the 2006–2007 season. Values were determined from five microlysimeters within the tree zone per irrigation treatment. $^{**}P < 0.05$ and $^{***}P < 0.01$.

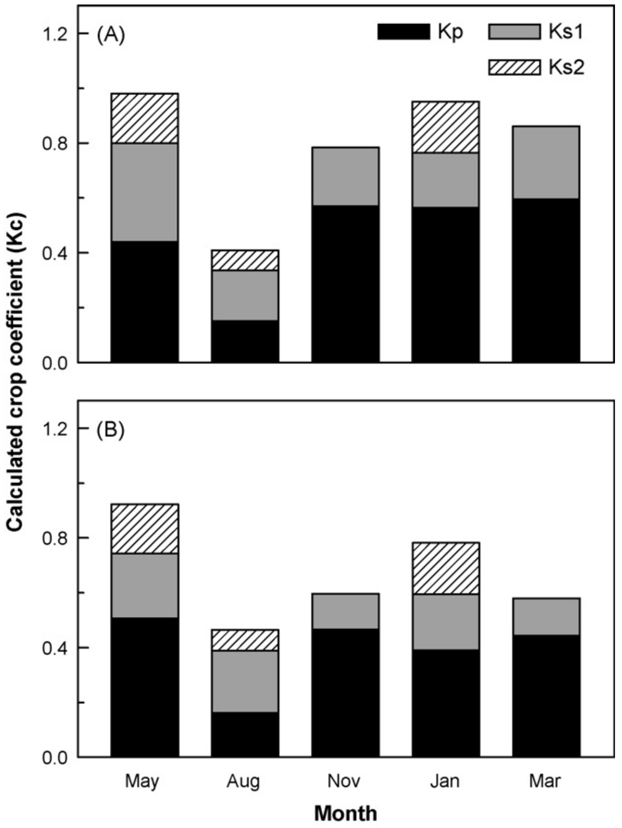

Fig. 4. Calculated crop coefficients (Kc) for plant transpiration (Kp), soil evaporation in the tree zone (Ks1), and inter-row soil evaporation (Ks2) during the 2006–2007 season for the highly (A) and moderately irrigated (B) treatments. The coefficients were calculated using the ETo over bare soil.

We assessed whether daily sap flow per unit leaf area (kg $m^{-2}\ d^{-1}$) was related to different environmental variables using regression analysis. Both treatments were pooled together because preliminary analysis did not indicate differences between treatments on a leaf area basis. Several environmental variables including ETo, average daily temperature, VPD, and solar radiation all showed high r^2-values versus sap flow (Fig. 5). Potential evapotranspiration (non-reference over bare soil) had a linear relationship with sap flow per unit leaf area ($r^2 = 0.84$; $P < 0.01$), while the relationship between VPD and sap flow was exponential ($r^2 = 0.85$; Fig. 5B). In contrast, daily averaged temperature showed a bi-linear relationship with sap flow in which a threshold temperature value of 13 °C was detected ($r^2 = 0.93$; Fig. 5C). Below 13 °C, changes in air temperature were associated with small changes in sap flow. There was also a strong linear relationship between solar radiation and daily sap flow ($r^2 = 0.80$; Fig. 5D), but the fit was not good for low solar radiation values.

We compared daily estimates of transpiration from the sap flow measurements with transpiration calculated from the model

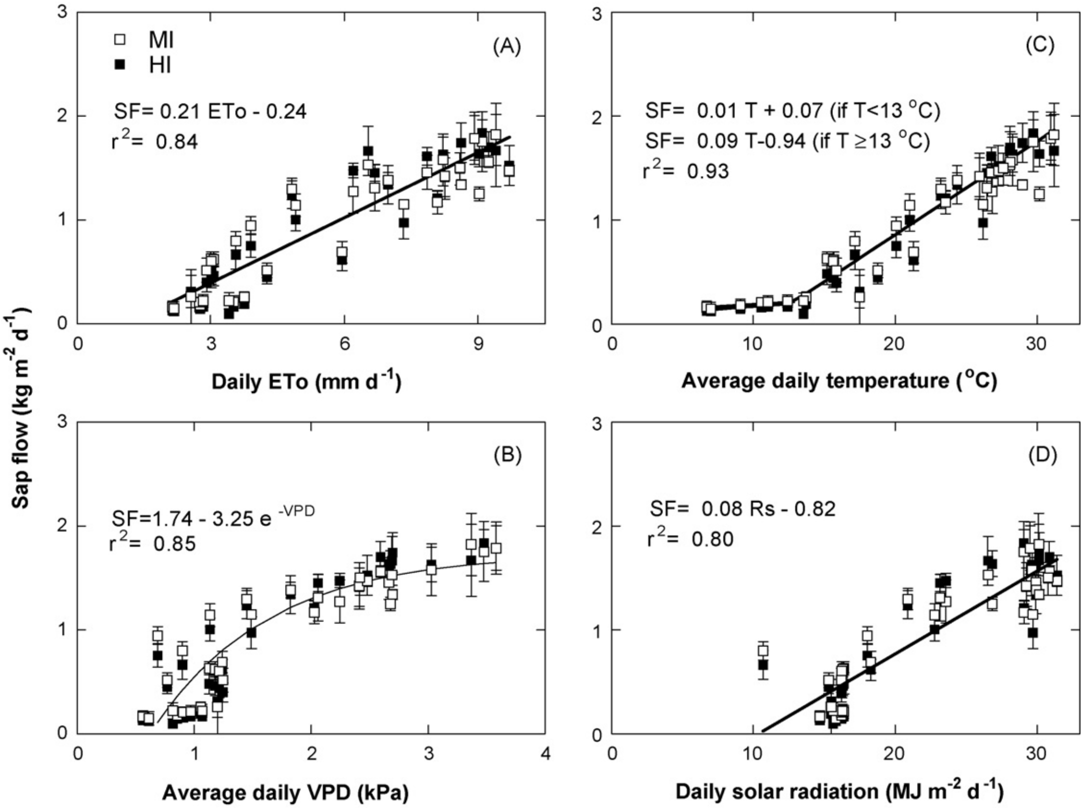

Fig. 5. Daily values of sap flow per unit leaf area as a function of the potential evapotranspiration over bare soil (A), average daily vapor pressure deficit (B), average daily temperature (C), and daily solar radiation (D). The moderately (MI) and highly irrigated treatments (HI) were pooled together for the regression analysis because the initial relationships did not differ between treatments. $n = 3$ Replicates per irrigation level with means ± standard error.

proposed by Orgaz et al. (2007). A good agreement was found between the observed and calculated data for the HI treatment except during the winter (August) when average calculated transpiration was greater than the observed (Fig. 6A). For the MI treatment, calculated transpiration values were higher than the observed during the winter as well as during the summer period (Fig. 6B).

4. Discussion

The expansion of olive plantations in northwestern Argentina and the consequent increase in demand for groundwater requires a better understanding of the components of water use (i.e., canopy transpiration and soil evaporation) in order to sustain production over the long-term. Daily transpiration values estimated from sap flow using the heat balance method ranged from 0.2 mm d^{-1} in the winter to 2.2 mm d^{-1} in the late-spring and summer for our 23% canopy cover. Corresponding values for a mature orchard with 50–60% canopy cover would be 0.5 and 4.8 mm d^{-1}. On a leaf area basis, daily transpiration values were about 1.5 l m^{-2} d^{-1} during the warmer months under high ETo conditions, and are similar to values reported by Fernández et al. (2006) for cv. 'Manzanillo' using the compensation heat pulse method (i.e., 1.6 l m^{-2} d^{-1}). On a basal trunk area basis, our values were generally about 25% higher than the heat pulse-measured values of Tognetti et al. (2004) for cv. 'Kalamata' under fairly similar ETo conditions, but basal trunk area and leaf area may not be tightly correlated. Larger differences with Tognetti et al. (2004) were seen during the winter months. However, the determination of sap flow at low rates is likely to become less accurate using either the stem heat balance or compensation heat pulse method (Grime and Sinclair, 1999).

The proportion of water used by plant transpiration relative to ETo (non-reference over bare soil) was relatively constant (i.e., Kp of 0.55–0.60) for much of the growing season under the HI treatment conditions although lower values were measured during the second fall measurement period (Kp of 0.44) and during the winter when Kp dropped to 0.15. This drop in Kp during the winter supports our earlier observation that a Kc of 0.3 could be used during the winter without negatively affecting olive production (Rousseaux et al., 2008). In contrast, soil evaporation and thus Ks fluctuated greatly throughout the year, and rainfall was a major factor in the variations of Ks and consequently of the overall Kc (Kp + Ks). For example, Ks was around 0.20 under the HI treatment in the spring (November) with no inter-row evaporation due to rainfall, but summer rainfall in January increased the Ks to 0.39. Testi et al. (2006a) similarly reported the sensitivity of overall Kc to rainfall based on differences in soil evaporation when comparing water losses from two olive orchards in Spain and California. When rainfall or excessive irrigation as occurred in May (fall) were not important factors, plant transpiration represented 70–80% of water lost to the atmosphere and soil evaporation represented 20–30% depending on the irrigation level. Bonachela et al. (2001) simulated that soil evaporation was responsible for 20% of water loss for a drip irrigated mature olive orchard in Cordoba, Spain with 10% of the ground area wetted by the emitters. In our experiment, the emitters wetted 6% and 12 % of the total surface for the MI and HI treatments, respectively.

Comparisons of monthly Kc values between our region and those of the Mediterranean Basin or California can be difficult because of the differences in rainfall distribution (i.e., winter vs. summer precipitation) and lack of standardized meteorological stations in our region. When our calculated Kc values are adjusted to reference (grass) ETo conditions, the Kc is about 0.85–0.90 under

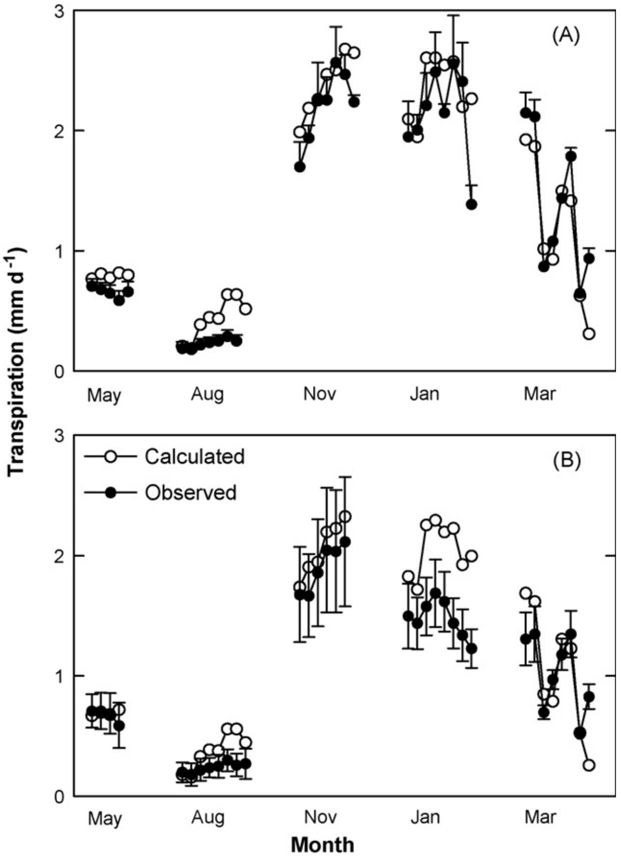

Fig. 6. Daily values of plant transpiration estimated from sap flow (observed) and calculated from the model of Orgaz et al. (2007) for the highly (A) and moderately irrigated (B) treatments. Observed values represent the average of $n = 3$ trees per irrigation treatment at each measured date.

highly irrigated conditions and 0.65–0.70 under the more moderate irrigation treatment. These values encompass the 0.77 value for Kc calculated by Testi et al. (2006a) for a high density orchard in Cordoba, Spain. Several field studies under Mediterranean climate conditions have shown that olive production is maximized within a range of Kc values from 0.60 to 0.80 (Goldhamer et al., 1993; Girona et al., 2002; Moriana et al., 2003) as does a recent experiment in our region (Correa-Tedesco, unpublished). It is likely that the HI treatment received more irrigation than was needed to maximize canopy transpiration, and that calculated Kc values were higher than might be expected due to elevated soil evaporation. Currently, the Kc recommended by FAO (Allen et al., 1998) is 0.7.

Daily sap flow per unit leaf area (kg $m^{-2}\,d^{-1}$) was strongly associated with meteorological parameters such as non-reference and reference ETo, average daily VPD, average daily air temperature, and solar radiation although the form of the relationship differed between parameters. A positive linear relationship between sap flow and ETo or VPD was reported by Tognetti et al. (2004) for olive. In our case, an exponential curve with VPD better represented the relationship with sap flow than a linear relationship for a similar range of VPD. The environmental variable that best explained the variability in sap flow per unit leaf area in our experiment was the average daily air temperature using a bi-linear model where sap flow increased strongly with air temperatures over 13 °C, but was relatively insensitive below this threshold temperature. A linear relationship between the normalized transpiration per unit of intercepted PAR and the mean air temperature for olive was proposed by Orgaz et al. (2007) although only air temperatures between 12 and 35 °C were evaluated. Our low response of sap flow to air temperature under 13 °C could be related to changes in sap viscosity and osmolarity at low temperatures (Améglio et al., 2004) or bulk canopy conductance may respond to seasonal variations independent from the direct meteorological effect on the stomatal response (Testi et al., 2006b). Pavel and Fereres (1998) suggested that low soil temperatures in the winter substantially increase root hydraulic resistance, which may result in greater insensitivity of sap flow to air temperature. Potential inaccuracies of sap flow measurements at low flows should also be further evaluated.

Our estimates of daily plant transpiration from sap flow for the two irrigation regimes are in good agreement with the transpiration model proposed by Orgaz et al. (2007). This model uses the intercepted fraction of daily PAR estimated from a function for canopy volume, mean daily vapor pressure deficit, and the average daytime air temperature to estimate canopy conductance and then transpiration. As suggested by Fernández et al. (2008), the reliability of such computer modeling rests on a good knowledge of plant leaf area. Because the plant canopies in our region are often not heavily pruned (i.e., LAD $> 2\ m^2\ m^{-3}$), we used our own estimated leaf area values rather than the function suggested by Orgaz et al. (2007). Additionally, we found that average daily temperature (i.e., 24-h averages) was in somewhat better agreement with our observed data. The only significant deviations with the model occurred during the winter measurement period when the model overestimated our observed data and during the summer when the model overestimated the values for the lower irrigation treatment possibly due to water stress. Other recently published models such as the general model of Pereira et al. (2006) and the olive-specific models of Fernández et al. (2008) and Yunusa et al. (2008) could also be tested, but such an evaluation is beyond the scope of this paper.

In the past 15–20 years, there has been a large expansion of surface area planted with olive in arid, subtropical Argentina (i.e., 30,000–90,000 ha). However, a local knowledge base for crop management is only starting to develop. A number of technologically advanced methods for irrigation scheduling such as maximum daily trunk shrinkage, soil water content capacitance sensors, and potentially sap flow are starting to be utilized in the more modern olive orchards, but lack of experience by the local producers and the high cost of the equipment currently limits their applicability. Thus, the FAO method for estimating ETc is still the method most often used, and crop coefficients appropriate for the region are paramount for growers. The validation of the Orgaz model under most climatic conditions for our region also provides an opportunity for the use of fairly simple mechanistic models by the agricultural sector.

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