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Research Paper: SW—Soil and Water

Water use, transpiration, and crop coefficients for olives (cv. Cordovil), grown in orchards in Southern Portugal

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To improve the scheduling of irrigation for low-density olive trees (*Olea europaea* L.) grown in a typical Mediterranean environment of Southern Portugal, and to clarify the mechanisms of water uptake by trees, transpiration, soil water status and stomatal response to water deficit were measured in an olive orchard. Olive trees of cv. Cordovil were subject to three irrigation treatments: full-rate irrigation, sustained deficit irrigation (SDI) providing for approximately 60% of water applied at full-rate irrigation, and a regulated deficit irrigation (RDI) with water applied at periods during three critical phases: before-flowering, at beginning of pit-hardening, before crop-harvesting to replenish soil moisture to field capacity. There was also a dry-farming treatment. Trees responded differently to summer rainfall and irrigation water: full-rate irrigation, which received 880 mm of irrigation and 240 mm of rainfall, used 704 mm for transpiration; SDI, which received the same amount of rainfall and 448 mm of irrigation water, used 745 mm of water for transpiration; RDI, which received 69 mm of irrigation water and 240 mm of rainfall, used 638 mm of water for tree transpiration; dry-farming, which received no irrigation, benefited from 240 mm of summer and early autumn rain and used 404 mm of water for transpiration. The results support the hypothesis that trees under RDI and dry-farming satisfy most of their early atmospheric evaporative demand by extracting water from outside of the area wetted by drip irrigation. Scaled-up orchard transpiration was used to define orchard crop and water stress coefficients. With full-rate irrigation and SDI the results showed that during summer droughts olive trees slow down their physiological mechanisms to conserve water, regardless of amount applied. The derived crop coefficient results also indicated that SDI was the most appropriate for scheduling the irrigation of cv. Cordovil orchards in Southern Portugal although applying RDI helped sustain orchard transpiration and yields. Irrigation accounted for 11% of total water used in transpiration, with the balance extracted by roots in the large volume of soil lying in the areas between the trees. However, using the RDI scheme to schedule irrigation appears to be appropriate only in wet years with well distributed late summer rainfall or where there is a shortage of farm irrigation water. In general, and particularly in years with no summer and early autumn rains as can often occur in this region, the SDI regime appears to be more appropriate for scheduling irrigation.

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Nomenclature

ΔS	variation in water storage in the root zone, mm
A_{cc}	average canopy area of the trees in the stand, m^2
A_{cm}	canopy area of the tree where sap flow was measured, m^2
A_{ct}	total canopy area of the olive tree population, m^2
Cp	specific heat of air, 1.013 $kJ\,kg\,°C^{-1}$
D	drainage, mm
Da	air vapour pressure deficit, kPa
EC	electric conductivity, $dS\,m^{-1}$
ET_0	FAO-Penman–Monteith potential evapotranspiration, mm
ET_c	crop evapotranspiration, mm
gc	canopy conductance, $mm\,h^{-1}$
h	water pressure head, cm
I	irrigation water, mm
Js	total sap flow rate, $m^3\,h^{-1}$
Js_{stand}	total sap flow rate of the stand, $m^3\,h^{-1}$
kc	crop coefficient
ks	water stress coefficient
n	number subscripts
R	measured rainfall, mm
r	sapwood depth, mm
R	trunk radius, mm
R	actual soil water content, mm
REW	relative extractable water
Rmax	soil water content at field capacity, mm
Rmin	minimum soil water content, mm
SWA	total sapwood area, m^2
T	stand transpiration, $l\,h^{-1}$
Ta	adjusted transpiration
Tc	canopy transpiration, $l\,s^{-1}\,m^{-2}$
t_{di}	trunk diameter, m
t_z	time elapsed after heat-pulse release, s
V_n	average corrected sap flow velocity, $m\,h^{-1}$
X_d	distance between heater probe and downstream temperature probe, mm
X_u	distance between heater probe and upstream temperature probe, mm
γ	psychrometric constant, 0.0673 $kPa\,°C^{-1}$
Δt	time interval, h
Δz	soil depth interval, cm
θ	soil water content, $m^3\,m^{-3}$
λ	latent heat of vaporisation, 2.45 MJ
ρ	density of air, $kg\,m^{-3}$
t_1	initial time interval, min
t_2	final time interval, min
z_1	initial depth interval, mm
z_2	final depth interval, mm
$K(h)$	hydraulic conductivity, $cm\,d^{-1}$
K_s	saturated hydraulic conductivity, $cm\,d^{-1}$
λ, α, n	fitting parameter
K	timescale duration, seconds or 3600 s for hourly time scales

1. Introduction

Olive trees are well adapted to the Mediterranean-type agro-ecosystems of Southern Portugal and have traditionally been cultivated in areas with no irrigation. According to the latest agricultural census (INE, 1999) the olive tree cultivation area in Portugal is around 335,029 ha, of which 148,402 ha are in the southern province of Alentejo and 37,298 ha in its sub-region of Moura, where the dry-farmed cultivars Cordovil, Verdeal and Galega are traditionally grown in orchards of around 100 trees ha^{-1}. The cultivar Cordovil is highly appreciated for its high fruit free fatty acid (oleic acid) content and the fine sensory properties of extracted oil. It is mainly responsible for the seal of quality ''Protected Designation of Origin (PDO)'' conferred to the olive oil coming from the region (CE, 2006); the result of a balanced blend of 35–40% Cordovil, 15–20% Verdeal and Galega oils. In recent year, because of the growing interest of farmers in increasing the size of their olive orchards to take advantage of the European Commission decision 2000/406/CE (Official Journal L 154, 27/06/2000 P. 0033-0033) to expand the Portuguese olive tree planting quota to 30,000 ha of new orchards, hundreds of drip irrigated high tree-density ($\geq$300 trees ha^{-1}) orchards of the cultivar Cobrançosa from north eastern Portugal and of the very high density ($\geq$1700 trees ha^{-1}) Spanish cultivar Arbequina have been established in the region. Dry-farmed cv. Cordovil orchards are traditionally widely spaced to take full advantage of the stored water from winter rains for spring and summer growth and were in the process of being converted to drip irrigation but they are now losing ground to newly introduced non-indigenous cultivars. This change has initiated a regional debate over the role of biodiversity and the preservation of the indigenous olive tree cultivars, the character of the local oil, and the need to increase the water use efficiency and the productivity of the Cordovil cultivar under irrigation (Anon, 2008a,b).

Because of the large range of summer rainfall, microclimate, soils and tree spacing in the olive growing areas, water requirements and the strategies used to irrigate olive trees vary widely. The literature contains few results on the irrigation of traditional, low-density olive orchards. Lavee *et al.* (1990) already showed that a single complementary irrigation of 75 mm following pit-hardening was effective in doubling olive production and oil yield in old olive trees of cv. Souri, when compared to rain-fed conditions. Pastor *et al.* (1999) reported an increase in yield in a 80 ha irrigated olive orchard compared to growth under rain-fed conditions, with no differences however between the irrigated treatments. In a low-density olive orchard of 69 trees ha^{-1} Moriana *et al.* (2007) showed that the trees in the water deficit and rain-fed treatments rapidly recovered from water stress after receiving irrigation water or autumn rainwater. They suggest that since recovery from water stress is rapid when irrigation is concentrated in the second half of the summer, this could allow efficient use of water in areas of limited available resources.

The current trend in the irrigation of olive trees is to develop either sustained deficit irrigation (SDI) or regulated deficit irrigation (RDI) strategies, whereby the water is applied at a rate less than the needs of evapotranspiration with only very small reductions in yield (Goldhamer, 1999; Tognetti et al., 2005). SDI applies a fixed fraction of the evapotranspiration rate throughout the irrigation season while RDI imposes a period of water stress that is controlled in terms of its intensity. At the onset of full bloom, which is the most sensitive period for olive trees, water supply should not be halted (Moriana et al., 2007). The second phase of fruit development, when pit-hardening occurs, has been identified as the most resistant to water deficit, which is when water supplies can either be reduced or halted (Goldhamer, 1999). Severe water stress during pit-hardening has been found to only reduce fruit and oil production slightly (Goldhamer et al., 1994; Moriana et al., 2003). The third phase of fruit development and oil accumulation is also very sensitive to water stress (Lavee and Wodner, 1991; Tognetti et al., 2005). The main advantages of RDI are the savings of water, the maintenance of high yields and the effects on olive oil quality. Under conditions of scarce water supply and drought, SDI and RDI irrigation regimes at selected phenological phases can lead to greater economic gains than simply maximising yields per unit of water as shown by Tognetti et al. (2006). However, they cautioned this approach requires precise knowledge of crop responses to water stress at specific physiological stages as drought tolerance varies considerably by genotype and growth stage.

Detailed information on plant water status is therefore essential when planning deficit irrigation practices for olive orchards (Fernández et al., 1997; Tognetti et al., 2006; Sofo et al., 2008). Water use strategies of olive trees are often affected by changes in environmental water status, radiation and temperature. Stomata close slowly as water deficit increases so that the photosynthetic rate can be maintained over a wide range of leaf water potential, and the stomatal response to vapour pressure deficit is attenuated in highly stressed plants (Fernández et al., 1997; Moriana et al., 2003; Moriana et al., 2007).

Both olive water consumption and the dynamics of transpiration and water uptake by main roots can be estimated from sap flow measurements (Fernández, 2006; Ortuño et al., 2006; Intrigliolo and Castel, 2006; Santos et al., 2007). The potential of this indicator for irrigation scheduling in olive was outlined by Fernández et al. (2001), who showed that this plant-based indicator uses the tree as a biosensor which responds to the soil water status, the plant characteristics and the atmosphere demands (Fernández et al., 1998; Green et al., 2003; Fernández, 2006). Tested to examine the robustness of the technique, the compensation heat-pulse method for measuring sap flow was deemed suitable for estimation of the short-time dynamics of transpiration, or changes in the hydraulic behaviour of the trees (Fernández et al., 2001).

Estimation of the transpiration of orchards and their water use on the basis of sap flow measurements in individual trees requires the scaling-up of data. A relationship between sap flow and selected biometric parameters that can be directly measured on trees in the field (Čermák et al., 2004) is often used, with the diameter at breast height or the basal area as the most commonly used. The biometric parameters must be directly measurable on a number of trees to represent the stand (Goodrich et al., 2000; Čermák et al., 2004; Gazal et al., 2006). Gazal et al. (2006) evaluated cottonwood stand transpiration based on individual tree sap flow, total sapwood area (SWA) and crown area of the cluster.

The aim of the present work was to establish the relationship between orchard olive transpiration from sap flow measurements and soil water status under full, sustained and RDI management, and to understand and improve the irrigation schedules of low-density olive trees of cv. Cordovil grown in typical Mediterranean environment of Southern Portugal. Such responses were used to quantify and predict stomatal conductance and to calculate crop and soil water stress coefficients for the orchard trees. The effect of environmental water status on olive tree stomatal conductance under the different water management was also examined.

2. Material and methods

2.1. *Experiment location, meteorological measurement and irrigation management*

The research was conducted during 2006 at the Herdade dos Lameirões located near Safara (lat. 38°04′57″N; long. 07°16′27″W; alt. 75 m), in the region of Moura, Alentejo, Portugal, using an orchard stand of mature olive trees (*Olea europaea* L. cv. Cordovil). The over 80 year-old mature olive orchard was planted on a 12 by 12 m spacing layout and was converted in 2005 from dry-farming to drip irrigation. The trees were treated from mid-March to the end of October 2006 using one of four irrigation treatments: a treatment A with full-rate irrigation of 77 trees to the full soil water holding capacity and continuously replenished, a SDI treatment B with irrigation of 64 trees to provide for approximately 60% of the water applied in treatment A, a RDI or treatment C in which water is applied to the 60 trees only during the three critical phase periods: before-flowering, at beginning of pit-hardening and before crop-harvesting, to provide enough water to replenish the soil moisture to field capacity, and a dry-farming treatment D. Reference evapotranspiration, ET_0 was calculated using the FAO-Penman–Monteith method and the procedures prescribed by Allen et al. (1998). Each tree was supplied with water by a single drip line with emitters spaced 1 m apart throughout the entire length of the emitter line placed at the soil surface and laid out along each tree row and serviced by twelve 3.6 $l\,h^{-1}$ emitters.

Weather data and rainfall events were collected by an automatic meteorological station placed within a few hundred metres from the olive orchard. Hourly averages of the meteorological parameters, wind speed, air temperature, solar radiation, precipitation and relative humidity were recorded and evaluated. Half-hour averages of the net radiation above the canopy of the trees were measured using one NrLite net radiometer (Kipp & Konen, Holland) connected to a data logger (Campbell CR10X, Campbell Scientific, Logan, UT, USA).

2.2. Sap flow measurements

To evaluate sap flow rates and transpiration, a representative tree in each treatment was selected and implanted with heat-pulse probes. Using the compensation heat-pulse technique (CHP) described in Green and Clothier (1988), Green *et al.* (2003) and Santos *et al.* (2007), sets of one heat source and two temperature probes were implanted in each sample tree at three different positions around the trunk. Sap flow measurements were taken at 30 min intervals during 8 months from March to end of October 2006 and tree transpiration rates were estimated as average sap flow rates of the three probes. Recorded sap flows were corrected for probe-induced wounding effects in the stem that cause disruption of xylem tissue near the probes.

2.3. Leaf area index and plant measurements

The leaf area index (LAI) was measured using a Digital Plant Canopy Imager CI-110 (CID, Inc., WA, USA). The trees chosen for LAI measurements were also monitored with sap flow probes. They came from a sample of 11 randomly chosen trees in each treatment.

Four images were taken from each tree canopy in opposite directions and the CI-110 software was used to determine the LAI for each tree considering the average of the four images taken.

2.4. Stomatal conductance estimates from sap flow measurements

Previous works of Santos *et al.* (2007) have shown that a noticeable decrease in measured olive tree sap flow rates occurs only when there is a considerable reduction in the soil water content. This indicates that transpiration rates of olive trees recently converted to irrigation are not sensitive to small variations in soil water content as the tree is still capable of extracting water from the soil and maintaining "normal" transpiration rates even under very low soil water contents. Stomatal conductance has been identified as a more sensitive indicator of olive tree water status (Fernández *et al.*, 1997; Moriana *et al.*, 2003; Tognetti *et al.*, 2006; Moriana *et al.*, 2007). Using the methods of Yunusa *et al.* (2008a,b) and sap flow measurements, the hourly stomatal conductance for the sampled trees for each treatment was calculated. The procedure described below to estimate stomatal conductance depends on local meteorological variables, measured sap flow and tree canopy variables.

Transpiration from the olive canopy, Tc can be calculated (Yunusa *et al.*, 2008b) using

$$\mathrm{Tc} = \frac{(\rho \cdot \mathrm{Cp}/\gamma) \cdot \mathrm{Da} \cdot \mathrm{gc}}{\lambda} K \tag{1}$$

where ρ is density of air (kg m^{-3}), Cp the specific heat of air (1.013 kJ kg °C^{-1}), γ psychrometric constant (0.0673 kPa °C^{-1}), Da is the vapour pressure deficit (kPa), λ is the latent heat of vaporisation (2.45 MJ kg^{-1}), gc is the canopy conductance and K is the timescale duration under consideration, which is daylight hours in seconds for the daily, or 3600 s for hourly, time scales. Assuming that canopy transpiration Tc (l s^{-1} m^{-2}) is equivalent to our measured sap flow for each tree, and that the vapour pressure deficit Da (kPa) and the density of air, ρ (kg m^{-3}) can be determined locally from meteorological measurements, the canopy conductance, gc can be expressed as function of transpiration Tc. Inverting Eq. (1), gc was estimated from the sap flow results in each sampled tree as

$$\mathrm{gc} = \frac{\mathrm{Tc} \cdot \lambda}{(\rho \cdot \mathrm{Cp}/\gamma) \cdot \mathrm{Da}} \frac{1}{\mathrm{K}} \tag{2}$$

Eq. (2) is an approximation of gc that applies when transpiration is strongly coupled to atmospheric conditions. These are appropriate assumptions for trees with relatively open canopies and under water supply as in the present study, and have been effectively used in a variety of vegetative types (McNughton and Jarvis, 1983; Fernández *et al.*, 1997; Ewers and Oren, 2000). Yunusa *et al.* (2008a) provide good comparison between measured and calculated gs under varying micrometeorological conditions. It presumes that Da in the bulk air above the canopy is the driving force for stand transpiration Tc, and that leaves are at the same temperature as the bulk air over the canopy. The term Tc/Da taken as the ratio of stand water flux to vapour pressure deficit is an indicator of the degree of stomatal opening at a given value of Da (Phillips and Oren, 1998; Ewers and Oren, 2000).

To replace the sap flow measurements in the canopy transpiration Tc variable in Eq. (2) the sap flow rate units were converted from l h^{-1} to l s^{-1} m^{-2} by dividing the sap flow rate of each tree by its canopy area. The deficit vapour pressure Da (kPa) was computed hourly using the data from the local automatic meteorological station and the procedures described in Allen *et al.* (1998). Finally, stomatal conductance gs for a given canopy conductance was estimated considering gc as in Yunusa *et al.* (2008a) the product of LAI and stomatal conductance, knowing that olives are hypostomatous.

2.5. Scaling of the sap flow and estimation of orchard transpiration

Olive orchard water uptake can be expressed as crop evapotranspiration, accounting for total water consumption by transpiration and soil evaporation, or solely as transpiration. This poses a problem because each treatment would require the monitoring of a large number of trees. A scaling-up process to achieve estimates of stand-level transpiration from individually sampled trees is often the only solution. To evaluate stand-level transpiration rates from measurements of individual-independent trees, the scaling method proposed in Gazal *et al.* (2006) was implemented. Stand transpiration *T* for each treatment was calculated based on individual tree sap flow, SWA, and the total canopy area of the tree plot. The total canopy area of the population of trees in each treatment was estimated from the average values taken from a sample of 11 randomly chosen trees. Table 1 presents the structural characteristics of the olive tree orchard (or stand), the computed total sapwood and canopy area of each treatment.

The SWA of all trees in the stand was determined considering a set of nine randomly chosen trees of different

Table 1 – Structural characteristics of the olive tree orchard (stand), computed total SWA, m^2 and canopy area for each treatment

Measured trees						Tree stand structural characteristics				
Treatment	Average trunk diameter, m	SWA, m^2	Canopy area, m^2 $tree^{-1}$	Trees	LAI	Average trunk diameter, m	Average SWA, m^2	Total SWA, m^2	Average canopy area, m^2 $tree^{-1}$	Total canopy area, m^2
A	0.40	0.055	27.34	77	1.187	0.39	0.058	4.56	17.44	1360.35
B	0.33	0.058	32.17	64	1.099	0.48	0.074	4.71	25.67	1643.19
C	0.50	0.077	40.15	60	1.101	0.46	0.070	4.21	21.15	1269.29
Dry-farmed	0.44	0.072	28.27	67	1.100	0.48	0.075	5.00	21.16	1417.51

trunk diameters where a linear relationship was observed between trunk diameter and the sapwood area, thus a linear equation was established defining SWA in m^2 as a function of the trunk diameter, t_{di} in m using

$$SWA = 0.1702t_{di} - 0.0076 \tag{3}$$

Each sampled tree equipped with sap flow probes had across its sapwood radial profile three probes with four thermocouple sensors each placed at 5, 12, 21 and 35 mm depth. Considering the average of the three probes in each tree, the total sap flow Js was computed as

$$Js = V_1SWA_1 + V_2SWA_2 + V_3SWA_3 + V_4SWA_4 \tag{4}$$

where Js is the total sap flow rate in $m^3\,h^{-1}$; V_n is the average corrected sap flow velocity at thermocouple sensor n in $m\,h^{-1}$; SWA_n is the sapwood area corresponding to the thermocouple sensor n in m^2 and n is the number subscripts at the four thermocouple sensor positions. The total sap flow rate of the stand Js_{stand} in $m^3\,h^{-1}$ in each treatment was divided by the SWA of the measured tree and multiplied by the SWA of the tree stand, SWA_{stand}

$$Js_{stand} = (Js/SWA)SWA_{stand} \tag{5}$$

To determine the transpiration T in $l\,h^{-1}$ of a hypothetical tree representing the average of the population in each treatment, the total sap flow of the stand Js_{stand} in $m^3\,h^{-1}$ was multiplied by 1000 to convert it to $l\,h^{-1}$, then divided by the canopy area A_{cm} in m^2 of the tree where sap flow was measured, and then multiplied by the average canopy area of the trees in the stand A_{cs} in m^2. Thus,

$$T = (1000\,Js_{stand})\,(A_{cs}/A_{cm}) \tag{6}$$

The daily transpiration T in $l\,day^{-1}$ was then determined by averaging and integrating in time the 30 min-interval measurements provided by the sap flow probes, consisting in a total of 48 measurements per day.

$$T = \sum_{n=1}^{47}\left(0.5\left(\frac{T_n + T_{n+1}}{2}\right)\right) \tag{7}$$

The daily transpiration T in $l\,day^{-1}$ was converted to ground-area based transpiration T in $mm\,day^{-1}$ dividing T by the total canopy area of the olive tree population A_{ct} in m^2

$$T\left(mm\ day^{-1}\right) = T\left(l\ day^{-1}\right)/A_{ct} \tag{8}$$

2.6. *Soil water measurements and crop evapotranspiration*

To evaluate soil moisture status in the 0.66 m diameter wetted areas produced by each of the twelve 3.6 $l\,h^{-1}$ emitters spaced 1 m apart in the 12 by 12 m tree layout and along the emitter line of the irrigation treatment, sets of Profile Probe-PR1 (Delta T Devices Ltd, Cambridge, UK) soil water content sensors were installed near the trunk of two representative trees in each treatment and at various depths into the soil. The profile probe sensors were placed in the wet areas around the tress located 1 and 3 m from the tree trunk along the tree drip line at depths of 0.10, 0.20, 0.30 and 0.40 m. Soil samples taken in the olive orchard indicate a clay soil at 0.45 m with a silt loam below and with a non-uniform and restrictive layer of very compact limestone and schist underneath which prevented the deeper placement of sensors. The average apparent bulk soil density was 1.58 $Mg\,m^{-3}$. Volumetric soil water content at field capacity (i.e. at -0.03 MPa) was 0.36 $m^3\,m^{-3}$ in the top layer and 0.34 $m^3\,m^{-3}$ in the root zone, whereas it was 0.27 $m^3\,m^{-3}$ in the top layer and 0.24 $m^3\,m^{-3}$ in the root zone at wilting point (i.e. at -1.5 MPa).

Crop evapotranspiration, ET_c in mm was obtained from the soil water balance in the root zone using the following equation defined for a given time Δt as

$$ET_c = R + I - D \pm \Delta S \tag{9}$$

where ΔS is the variation in water storage in the root zone in mm; R is the measured rainfall in mm; I is the irrigation amount in mm; D is the drainage in mm. A negligible water runoff from irrigation was recorded. The variation in water storage ΔS between 0 and 0.45 m depth and within a time interval Δt was obtained using Eq. (10).

$$\Delta S = \int_{z_1}^{z_2} \theta(z, t_1)\,dz - \int_{z_1}^{z_2} \theta(z, t_2)\,dz \tag{10}$$

where z_1 is the initial depth interval in mm; z_2 is the final depth interval in mm; t_1 is the initial time interval in min and t_2 is the final time interval in min. Drainage below the root zone required for Eq. (9) was estimated using Eq. (11), where $K(h)$ is the hydraulic conductivity in $cm\,d^{-1}$ at the corresponding water pressure head h of the soil layer.

$$D = K(h)\frac{\Delta(h + z)}{\Delta z}\Delta t \tag{11}$$

The unsaturated hydraulic conductivity $K(h)$ of Eq. (11) was estimated using Eq. (12) (van Genuchten, 1980)

$$K(h) = K_s \frac{\left(\left(1+(\alpha h)^n\right)^{1-1/n} - (\alpha h)^{n-1}\right)^2}{\left(1+(\alpha h)^n\right)^{(1-1/n)\ (\lambda+2)}} \quad (12)$$

where K_s is the saturated hydraulic conductivity in cm d^{-1}, h is the water pressure head in cm at which $K(h)$ is being calculated and λ, α and n are fitting parameters. More details on procedure, soil characteristics and associated soil parameters were given by Santos *et al.* (2007) and Fares and Alva (2000).

3. Results and discussion

3.1. Irrigation and orchard transpiration

In 2006 the summer distribution of rainfall was highly favourable for growing trees (Table 2), with frequent light rains during the usually dry summer months and considerable rainfall in September, when olives in the final stage of maturation and oil accumulation need irrigation or rainfall (Moriana et *al.*, 2007). Treatment A received 880 mm of irrigation from mid-March through to October (Table 2) to provide for adequate water in the soil profile, satisfying the atmospheric water demand of the trees. A sustained deficit was induced to treatment B which received 448 mm of irrigation water. The regulated deficit scheduled for treatment C was only accomplished before-flowering, when 29.1 mm of water was applied between April 29 and May 26 and at beginning of pit-hardening, when 33.4 mm of water was applied on July 3rd for a week thereby raising the soil moisture to field capacity. Early autumn rains in September and October, just before crop-harvesting, precluded the need to provide for the scheduled irrigation before crop-harvesting. The dry-farming treatment D received no irrigation water and fortunate to receive 240 mm of well distributed summer rainfall and early and abundant autumn rains.

The daily total sap flow of olive stand orchards at the experimental site (Fig. 1) reflected the structural characteristics of the tree cluster in each treatment (Table 1) and the irrigation regime imposed. Table 3 shows the accumulative orchard transpiration values for each treatment, with a total of 704 mm for treatment A, 745 mm for treatment B, 638 mm for treatment C and 404 mm for treatment D. They were higher for treatment B and noticeably different from values of treatment A which received approximately 40% more water throughout the growing season. A marked decline in sap flow values for treatment C was observed during the peak of summer drought following the irrigation events in July. However, the application of 29.1 mm of water in May and 33.4 mm in July sustained sap flow at substantially higher rates than the observed for treatment D, whose values stayed low throughout the irrigation season. Individual monitored tree transpiration values were 657 mm for treatment A, 599 mm for treatment B, 726 mm for treatment C and 373 mm for treatment D.

The trees responded differently to the summer rainfall and the irrigation water. Treatment A that received 880 mm of irrigation and 240 mm of rainfall only needed to mobilise 63% of that total for the total growing seasonal transpiration of trees. Treatment B, which received the same rainfall as treatment A but 51% of its irrigation water, was able to extract and use 745 mm of water from the soil. The sparse but well distributed summer rainfall and the early rains of September and October helped to maintain and stabilise the transpiration rates of treatment C during the irrigation period. Receiving only 69 mm of irrigation water and 240 mm of rainfall, treatment C was able to mobilise and use a total of 638 mm of water for tree transpiration, 106% more water than the combined amount supplied with irrigation and rainfall. Some features of the olive root system, as observed by Fernández *et al.* (1991, 1994), give it a high adaptability to water stress conditions and the capability to explore large volumes of soil for water. Sofo *et al.* (2008) also report that olive plants subjected to water deficit can lower the water content and potential of their tissues, thereby establishing a particularly high potential gradient between leaves and roots, stopping canopy growth but not photosynthetic activity and transpiration. Differences in the structural characteristics of the trees (Table 1) monitored in treatment C, including tree diameter and canopy area, may explain the differences observed in the transpiration when compared with treatments A and B.

Table 2 – Accumulated values of rainfall, reference evapotranspiration ET_0 and applied irrigation for each treatment, during 2006

Start	End	ET_0, mm	Rainfall, mm	Irrigation, mm A	Irrigation, mm B	Irrigation, mm C
18-Mar	31-Mar	33.5	44.4	4.7	2.4	3.2
01-Apr	15-Apr	45.0	19.9	4.7	2.4	3.2
16-Apr	28-Apr	41.4	9.8	15.8	8.1	0.0
29-Apr	12-May	58.6	0.0	33.2	16.5	22.6
13-May	26-May	73.0	0.5	42.7	21.8	6.5
27-May	09-Jun	79.0	0.0	47.4	24.2	0.0
10-Jun	24-Jun	79.0	49.2	39.5	20.1	0.0
25-Jun	06-Jul	69.8	0.0	44.2	22.6	22.6
07-Jul	19-Jul	82.3	11.5	79.0	40.3	10.8
20-Jul	03-Aug	97.3	0.0	113.8	58.0	0.0
04-Aug	17-Aug	84.6	13.1	110.6	56.4	0.0
18-Aug	09-Sep	124.7	2.3	178.6	91.0	0.0
10-Sep	25-Sep	61.7	22.2	75.8	38.7	0.0
26-Sep	20-Oct	72.2	67.5	90.1	45.9	0.0
	Totals	1002.1	240.4	880.1	448.4	68.9

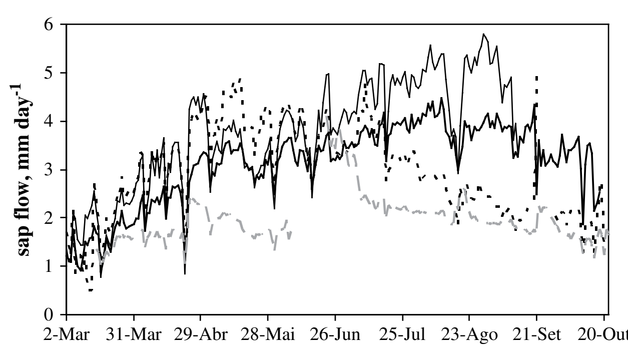

Fig. 1 – Sap flow (mm day^{-1}) for each treatment after scaling the results to orchard-level average conditions: treatment A, ——; treatment B, —; treatment C, - - - ; dry-farming, – – –.

Table 3 – Stand transpiration estimated from sap flow scaling method to replicate the transpiration from a hypothetical olive tree representative of the average structural characteristics of the cluster for each treatment

2006		Stand transpiration, mm			
Start	End	Treatment			
		A	B	C	Dry-farming
18-Mar	31-Mar	24.0	28.6	31.4	20.6
1-Apr	15-Apr	33.6	43.2	44.6	24.4
16-Apr	28-Apr	32.9	43.8	42.3	24.4
29-Apr	12-May	44.8	51.5	57.7	28.5
13-May	26-May	43.6	45.5	57.3	24.3
27-May	9-Jun	46.0	50.8	55.2	22.1
10-Jun	24-Jun	48.9	57.1	54.3	12.3
25-Jun	6-Jul	40.8	48.8	41.6	40.4
7-Jul	19-Jul	48.7	61.1	50.7	30.1
20-Jul	3-Aug	55.1	67.2	44.9	30.3
4-Aug	17-Aug	56.1	67.7	37.3	29.0
18-Aug	9-Sep	87.9	115.6	54.2	46.8
10-Sep	25-Sep	56.5	64.3	23.2	29.7
26-Sep	20-Oct	84.8	N/A	43.4	40.6
	Totals	703.6	745.3	638.0	403.5

The dry-farmed treatment D also beneficiated from summer and early autumn rains enabling it to mobilise and use 404 mm of water for transpiration when rainfall accounted for only 240 mm.

3.2. *Olive tree water balance and consumptive use*

Table 4 shows the tree evapotranspiration ET_c rates estimated from the soil water balance for treatment A. The daily transpiration rates from sap flow measurements and the daily applied irrigation rates are also included. Table 5 presents similar values obtained for treatment B and similar data for treatment C are shown in Table 6.

According to the prescribed water application, treatment A trees received continuous irrigation water throughout the season, with daily rates increasing gradually up to 7.9 mm in August. Initially, by taking advantage of winter water stored in the soil, the trees were able to maintain transpiration rates above the applied irrigation rate until May 12. The irrigation rates were lower than the transpiration rate values until May 12 probably because the profile probe sensors are unable to capture the dynamics of tree root-water extraction outside the wet area of the drip irrigation emitters, particularly when the surrounding soil moisture is high and is available for crops. The sensors work considerably better when irrigation becomes the main source of water for the sampled soil volume and the surrounding soil moisture is low. This was demonstrated from May 19 to the end of September when there was a closer match between ET_c and the irrigation applied. As indicated earlier, in response to atmospheric water demand, the trees were able to maintain transpiration rates above the applied irrigation rate until May 12. Thereafter, the transpiration rates closely matched the irrigation water applied until June 6 when they began to slowly decline despite the amounts of applied water. The T to I ratio approached 0.5 at the end of July and this dropped to 0.48 in August and to 0.47 in September. This suggests that an excess of irrigation water was applied in this treatment, and from the end of June onwards water was lost by soil evaporation. After June 26, ET_c to I ratios of 1.0, or slightly higher, confirm the daily average of 3.7–4.0 mm of water consumed by soil evaporation during this period. The sustained high level of relative extractable water (REW) during the course of irrigation season (0.99–0.89) also indicates that water was lost by soil evaporation. REW was calculated as

$$\mathrm{REW} = (R - \mathrm{Rmin})/(\mathrm{Rmax} - \mathrm{Rmin}) \tag{13}$$

Table 4 – Crop tree transpiration estimated during year 2006 from sap flow measurements for the mature olive tree under full-rate irrigation (treatment A) during the period considered and corresponding crop evapotranspiration ET_c rates per tree estimated from soil water balance using the Delta T PR1 soil moisture sensor probe placed in the wet bulb developed by drip irrigation emitters

Date interval		Mature olive tree treatment A (canopy area = 27.34 m^2)			
Start	End	Transpiration from sap flow rates, $l\,d^{-1}\,m^{-2}$	ET_c from soil water balance with profile probe, $l\,d^{-1}\,m^{-2}$	Daily average irrigation, $l\,d^{-1}\,m^{-2}$	REW
18-03-2006	31-03-2006	1.6	0.9	0.34	0.86
01-04-2006	15-04-2006	2.1	0.8	0.32	0.82
16-04-2006	28-04-2006	2.4	0.8	1.21	0.82
29-04-2006	12-05-2006	3.0	2.4	2.37	0.88
13-05-2006	26-05-2006	3.0	3.3	3.05	0.92
27-05-2006	09-06-2006	3.1	3.0	3.39	0.92
10-06-2006	24-06-2006	3.1	3.1	2.63	0.92
25-06-2006	06-07-2006	3.2	3.8	3.69	0.88
07-07-2006	19-07-2006	3.6	5.6	6.08	0.87
20-07-2006	03-08-2006	3.8	7.9	7.59	0.90
04-08-2006	17-08-2006	3.8	8.0	7.90	0.95
18-08-2006	09-09-2006	3.7	7.7	7.76	0.98

REW corresponds to the average REW in the wet bulb.

Table 5 – Crop tree transpiration estimated during year 2006 from sap flow measurements for the mature olive tree under full irrigation (treatment B) during the period considered and corresponding crop evapotranspiration ET_c rates per tree estimated from soil water balance using the Delta T PR1 soil moisture sensor probe placed in the wet bulb developed by drip irrigation emitters

Date interval		Mature olive tree treatment B (canopy area = 32.17 m^2)			
Start	End	Transpiration from sap flow rates, $l\,d^{-1}\,m^{-2}$	ET_c from soil water balance with profile probe, $l\,d^{-1}\,m^{-2}$	Daily average irrigation, $l\,d^{-1}\,m^{-2}$	REW
18-03-2006	31-03-2006	1.6	0.6	0.17	0.89
01-04-2006	15-04-2006	2.2	0.5	0.16	0.82
16-04-2006	28-04-2006	2.6	0.5	0.62	0.82
29-04-2006	12-05-2006	2.8	1.1	1.18	0.76
13-05-2006	26-05-2006	2.5	1.6	1.55	0.84
27-05-2006	09-06-2006	2.8	1.7	1.72	0.88
10-06-2006	24-06-2006	2.9	1.7	1.34	0.85
25-06-2006	06-07-2006	3.1	2.0	1.88	0.83
07-07-2006	19-07-2006	3.6	2.9	3.10	0.76
20-07-2006	03-08-2006	3.7	4.0	3.87	0.91
04-08-2006	17-08-2006	3.7	4.0	4.03	0.79
18-08-2006	09-09-2006	3.9	4.0	3.96	0.87

REW corresponds to the average REW in the wet bulb.

where *R* is the actual soil water content, mm; Rmin is the minimum soil water content measured during the experiment, mm; Rmax is the soil water content at field capacity, mm.

In contrast, treatment B maintained the same rate of tree transpiration as treatment A throughout the irrigation season, using in the process the entire amount of daily water supplied to the treatment by irrigation. Values for *T* to *I* ratio of 1.0 or higher support this and indicate that virtually no soil evaporation took place. Estimates for ET_c, from profile probe sensors also rose steadily from beginning of irrigation in March and closely followed the irrigation applied. Tree transpiration rates stayed slightly above estimated ET_c values from March to July 19 as trees used irrigation water and soil water stored outside the wet area of the drip emitters. Thereafter, the rates were closely matched indicating that all the irrigation water and some rainfall was used for tree growth, with hardly any lost *via* non-physiological processes such as runoff or soil evaporation. Recorded REW stayed between 0.76 and 0.91 (Table 5). Almost the same amount of water was used through transpiration in treatment A and treatment B suggesting that olive trees, adapted to prolonged periods of drought that occur during summer in the Mediterranean basin, have developed a series of mechanisms to slow down their physiological processes and improve water use efficiency. This process is identified by the lower average crop coefficient values (0.6–0.7

Table 6 – Crop tree transpiration estimated during year 2006 from sap flow measurements for the mature olive tree under full irrigation (treatment C) during the period considered and corresponding crop evapotranspiration ET_c rates per tree estimated from soil water balance using the Delta T PR1 soil moisture sensor probe placed in the wet bulb developed by drip irrigation emitters

Date interval		Mature olive tree treatment C (canopy area = 40.15 m^2)			
Start	End	Transpiration from sap flow rates, $l\,d^{-1}\,m^{-2}$	ET_c from soil water balance with profile probe, $l\,d^{-1}\,m^{-2}$	Daily average irrigation, $l\,d^{-1}\,m^{-2}$	REW
18-03-2006	31-03-2006	2.5	0.6	0.23	0.91
01-04-2006	15-04-2006	3.3	0.3	0.21	0.84
16-04-2006	28-04-2006	3.6	0.3	0.00	0.84
29-04-2006	12-05-2006	4.5	1.5	1.61	0.61
13-05-2006	26-05-2006	4.5	0.6	0.46	0.86
27-05-2006	09-06-2006	4.3	0.2	0.00	0.51
10-06-2006	24-06-2006	4.0	0.3	0.00	0.39
25-06-2006	06-07-2006	3.8	1.6	1.88	0.41
07-07-2006	19-07-2006	4.3	1.2	0.83	0.93
20-07-2006	03-08-2006	3.5	0.2	0.00	0.44
04-08-2006	17-08-2006	2.9	0.0	0.00	0.29
18-08-2006	09-09-2006	2.6	0.1	0.00	0.21

REW corresponds to the average REW in the wet bulb.

or lower) attributed to olive trees from June to September (Fernández, 2006), as trees use their inbuilt mechanisms to temporarily shut down their physiological systems until the cooler temperatures of late summer or early autumn arrive. It appears that during this resting phase applying water to treatment A in excess of that needed to sustain tree transpiration was inefficient for vegetative growth and it stimulated losses through soil water evaporation.

Daily transpiration rates for treatment C (Table 6) were unexpectedly high throughout the season, being similar to the values of treatments A and B, despite receiving much lower irrigation water in May (29.1 mm) and later in July (33.4 mm). As noted earlier, September and October rains just before crop-harvesting precluded the need to provide for irrigation. Much higher daily transpiration values than crop evapotranspiration estimates may also be caused by the use of rainfall water stored in the soil outside the zone of the drip irrigation emitters and the ability of roots to explore and extract soil water at depths and in the large soil volumes because of the 12 m by 12 m tree spacing. This ability was recognised by Fernández *et al.* (1991, 1997) in olive trees and by Rana *et al.* (2004) in vineyards, as a process that allows trees to get their water supply during drought periods. Modelling studies show that predicting ET_c based only on root zone averaged soil moisture may be an oversimplification, particularly if plants can compensate for a portion of their roots being in dry soil (Guswa et al., 2002). REW decreased gradually to a value of 0.39 in the middle of June, only to increase to a value of 0.93 after the irrigation events at the beginning of July. From there on, and in the absence of irrigation water or rainfall, the REW of treatment C dropped steadily until middle August, where the 13.1 mm of rainfall restored it to higher values for a short while. A more sustained recovery was established at the end of September when more regular rains brought soil water storage back to around 100 mm (Table 6). The structure of the trees monitored in treatment C, with their much larger canopy area, diameter trunk and subsequently root system, may be responsible for the increase in sap osmotic pressures enabling the roots to extract more water when the soil dries as suggested by Abd-El-Rahaman *et al.* (1966), or for establishment of a higher water potential gradient between canopy and root system (Tombesi *et al.*, 1986).

Trees from the dry-farming treatment also benefitted from the same mechanisms to supply their water requirements during the drought periods (Table 3). However, not being irrigated, their transpiration values are lower than those of treatment C. As for treatment C, in a favourable wet year the trees sustained remarkably high daily transpiration rates. These rates could not be explained by evapotranspiration rates calculated from the probe soil moisture sensors (data not shown).

3.3. *Orchard crop and water stress coefficient*

Fig. 2 shows the average seasonal T/ET_0 calculated separately for each treatment to account for each stand characteristics and the water applied. Larger T/ET_0 values occur in March and April when the moisture stored in the soil from winter rains and first irrigation events was still high. As drought from summer months occurs, regardless of the water applied, the olive trees slowed down their physiological mechanisms to conserve water and their T/ET_0 ratio was reduced. It is worthwhile noticing that despite the large amount of water applied to treatment A throughout the summer drought (Table 4), T/ET_0 ratio declined to values as low as 0.6. With an unlimited supply of water, treatment B received adequate amounts of irrigation water to compensate for transpiration (Table 5) and showed a decline in T/ET_0 values during the same months but to slightly higher values than treatment A.

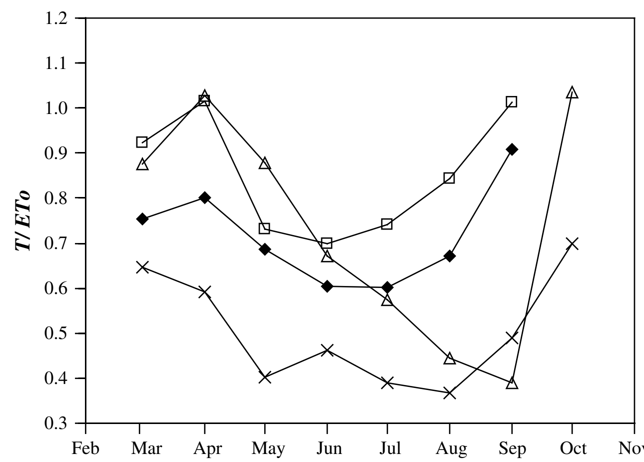

Fig. 2 – T/ET_0 values, estimated as the ratio between the scaled transpiration for each treatment, mm day^{-1} and Penman–Monteith ET_0, mm day^{-1} computed by the local meteorological station: ◆, treatment A; □, treatment B; △, treatment C; ×, dry-farming.

T/ET_0 values for treatment B are similar to the crop coefficient (kc) values for olive trees obtained by Fernández (2006) for the well-watered ''Manzanilla de Sevilla'' trees near Sevilla, southern Spain, planted at 7 m × 5 m spacing. The values for treatment B were higher than the values of 0.38 and 0.39 obtained in July and August, respectively by Orgaz and Pastor (2005) for mature ''Picual'' trees near Cordoba, southern Spain. Sevilla is much closer to our experimental site. It also has a climate that is more similar to Moura than Cordoba which is more peninsular. Nonetheless, all values reflect the summer rest period of the olive trees and the more intense transpiration activity in the months preceding and following rest, when crop coefficient values approach unity.

Table 7 – Monthly water stress coefficient ks for RDI and dry-farmed treatments as the ratio of their Ta/ET_0 estimates to corresponding T/ET_0 values for the well-watered treatment

	RDI	Dry-farming
Mar	0.96	0.70
Apr	1.00	0.59
May	1.20	0.55
Jun	0.96	0.66
Jul	0.77	0.53
Aug	0.52	0.44
Sep	0.39	0.49
Oct	1.00	0.70

When plants are under water stress the standard transpiration is reduced and the crop coefficient is adjusted to those conditions using a water stress coefficient ks (Allen *et al.*, 1998). The adjusted transpiration rate, Ta, is the product of kc, ks, and ET_0. The coefficient ks is often used in irrigation scheduling schemes to adjust the measured ET to reflect soil water conditions. Table 7 presents the monthly estimated ks water stress coefficient for treatments C and D, where there was water deficit, using the ratio of their Ta/ET_0 estimates to compare with the T/ET_0 values for treatment B. Soil evaporation is taken as zero as all estimates of tree evapotranspiration either closely match the transpiration rates of treatment B or are lower (treatments C and D). The results confirm the steadily decline in transpiration rates of treatment C from May to September, when transpiration dropped to 39% of treatment B. The dry-farmed orchard, that benefitted from the same amount of rainfall but was not irrigated, showed much sharper decline in the water stress coefficient from May to October. Comparing treatments B and C, results confirm that by March, when the stress coefficient was 0.7, the stored moisture in the soil from the winter rains was already not sufficient to increase the dry-farmed transpiration rates to values close to those of treatment C. Irrigating treatment C in that period maintained tree transpiration rates high until June, at around 96% of treatment B, which is in contrast to the estimated 66% value for the dry-farmed orchard. Likewise, irrigating treatment C in July helped sustained water stress to values close to 77% of treatment B. It is worthwhile recalling that treatment C also took advantage of the high annual rainfall and early autumn rains which enable most of the atmospheric evaporative demands of the treatment to be from water extracted from outside of the area wetted by the drip irrigation emitters. Also autumn rains in September and October, just before crop-harvesting, precluded the need to provide for the scheduled irrigation. Similar experiments conducted by Santos *et al.* (2007) in the drier year of 2005, where there was no significant rainfall in August and early September and scarce farm water resources that caused irrigation to be proscribed during those months, showed a much more significant reduction in transpiration rates.

3.4. *Stomatal conductance and orchard productivity*

Olive trees, being sensitive to high air vapour pressure deficit Da, avoid periods of excessive transpiration drought by regulating stomatal conductance (Moriana *et al.*, 2003; Moriana *et al.*, 2007; Yunusa *et al.*, 2008a). A proportional decrease in stomatal conductance, gs with increasing Da for values of up to approximately 3.5 kPa was reported by Fernández *et al.* (1997). However, Bongi and Loreto (1989) found little response of gs to Da whereas Giorio *et al.* (1999) found no correlation between gs and Da. We assessed the seasonal variations in stand-level stomatal aerodynamic conductance to vapour pressure deficit Da throughout the irrigation season to evaluate the responsiveness of trees in our irrigation treatments to atmospheric water demand. Fig. 3 shows the typical daily course of air vapour pressure deficit, Da and net radiation, Rn in the experimental site in the months from June to September when there was irrigation. Rn and Da followed the same trend throughout the day, with steady rise of Rn in the early hours of the day and peaks at around 12:00 and 14:00 hour. Da lagged behind or followed the course of Rn and often peaked at latter times, usually between 16:00 and 18:00 hours. This daily cycle takes Da values rapidly to around 2.5 and 3 kPa in mid morning to as high as 5 kPa in the afternoon. The long term relationships between gs and Da, from April 2nd to May 17th, from May 18th to July 2nd and from July 3rd to August 29th, respectively were derived. Figs. 4, 5 and 6 present the best-fit relationships for the four treatments and time intervals. They were best described by power function using a non-linear least squares curve-fitting technique and by adjusting approximately 700 hourly gs data points per treatment with their counterparts of Da. Table 8 shows the adjusted best-fit equations and coefficients of determination (r^2) for the time intervals and treatments. R^2 give the proportion of variability in the dependent variable that can be explained by the independent variables (Sokal and Rohlf, 1995).

Although the diurnal variation of T closely tracked Rn, the stomatal openings as indicated by gs actually peaked early in the day and then rapidly decreased as Da increased. For all treatments stomatal conductance was also considerably depressed throughout the irrigation season until the end of August, as daily Da increased. It is worthwhile noticing the higher sap flow rates (Fig. 1) and stomatal conductance (Fig. 4 and 5) of treatment C from April 2nd to July 2nd than treatment A and B. This is when moisture content was high enough in the irrigated and surrounding soil volume to prevent serious drought stress (Table 7). From there, the stomatal conductance of treatment C progressively converged to that of treatments A and B values and transpiration concurrently

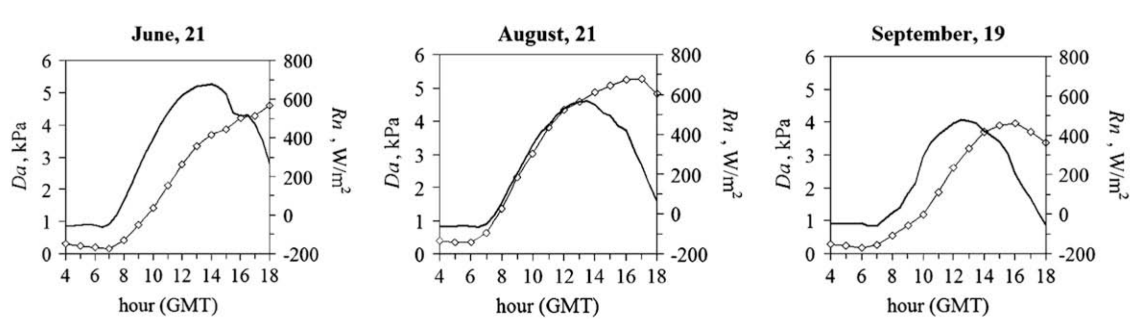

Fig. 3 – Typical daily trend in air vapour pressure deficit, Da and net radiation, Rn in the experimental site during irrigation months, from June to September. -◇-, air vapour deficit Da, kPa; —, net radiation, Rn, $W\,m^{-2}$ measured above the tree canopy.

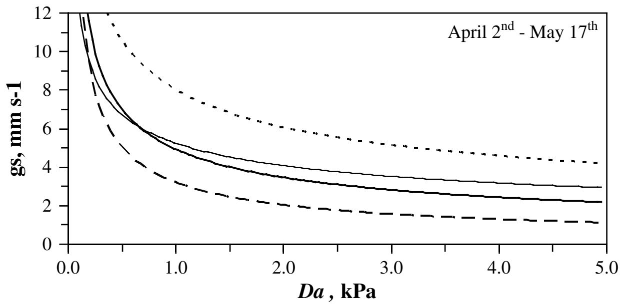

Fig. 4 – Best-fit relationship between stomatal conductance, gs and air vapour pressure deficit, Da from April 2nd to May 17th: ——, treatment A; —, treatment B; - - -, treatment C; – –, dry-farming at the Herdade dos Lameirões site. Da was determined for daylight hours (5:00–18:00 hour).

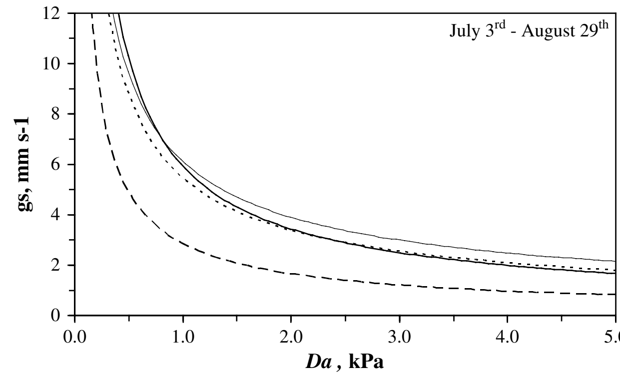

Fig. 6 – Best-fit relationship between stomatal conductance, gs and air vapour pressure deficit, Da from July 3rd to August 29th: ——, treatment A; —, treatment B; - - -, treatment C; – –, dry-farming at the Herdade dos Lameirões site. Da was determined for daylight hours (5:00–18:00 hour).

declined (Fig. 1 and Table 7), making it difficult to rank gs treatment values by order of amount of water supplied. Also, as summer progressed, as expected, the gs *vs*. Da values of treatment A and B almost always overlapped. The relatively higher values of gs *vs*. Da observed for treatment B than treatment A in Figs. 4, 5 and 6 might explain its higher sap flow values measured throughout the irrigation season (Fig. 1).

Table 9 shows the average olive orchard fruit production in 2006 and in 2004, when the orchard was still under dry-farming and prior to its conversion to irrigation in 2005. No significant differences in fruit production were obtained in 2006 among the irrigated treatments. However, the more restricted water treatment C averaged an unexpectedly high yield of 58.4 ± 8.4 kg tree^{-1}, probably because of the high stomatal conductance and sap flow rates observed from April 2nd to July 2nd. Moriana *et al.* (2007) had reported that the osmotic adjustment of olive trees can lead to large amount of water extracted from the soil, reducing the effect of irrigation in low-density olive orchards. Yet, in 2005, a drier year with no significant rainfall in August and early September and scarce water resources, a similar experiment (Santos *et al.*, 2007) conducted at the same site showed that in absence of water, treatment C had a highly significant reduction in tree fruit yield of 9.6 ± 6.4 kg tree^{-1}.

The above results might indicate that the prescribed RDI of treatment C is the most suitable for olive orchards during wet years with well distributed summer rainfall, when roots have available water to explore outside the wet area developed by the irrigation system, or in years where there is a shortage of farm water for irrigation. Drier years with no summer and early autumn rains occur frequently in the region.

Considerable differences were observed between the stomatal conductance of irrigated and non-irrigated treatments. Throughout the irrigation season trees of the dry-farmed treatment showed evidence of stomatal limitation with closing of the stomata under conditions of high air vapour pressure deficit to avoid excessive transpiration, maintaining low and relative constant values of gs around 2.0 mm s^{-1} for Da over 1.0 kPa. However, the highly favourable distribution of rainfall during the normally dry summer

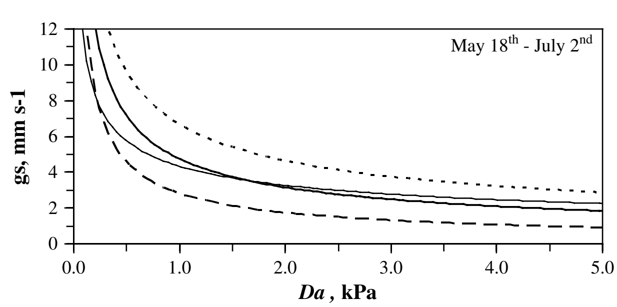

Fig. 5 – Best-fit relationship between stomatal conductance, gs and air vapour pressure deficit, Da from May 18th to July 2nd: ——, treatment A; —, treatment B; - - -, treatment C; – –, dry-farming at the Herdade dos Lameirões site. Da was determined for daylight hours (5:00–18:00 hour).

Table 8 – Adjusted power equation of best-fit stomatal conductance gs, mm s^{-1} *vs*. air deficit vapour pressure Da, kPa for treatment A, B, C and dry-farming in three different time intervals, April 2nd to May 17th, May 18th to July 2nd, and July 3rd to August 29th

Time interval	Treatment	Adjusted equation	r^2
April 2nd–May 17th	A	$gs = 4.9256Da^{-0.5092}$	0.9042
	B	$gs = 5.2371Da^{-0.3607}$	0.6641
	C	$gs = 8.003Da^{-0.3991}$	0.7604
	Dry-farming	$gs = 3.2081Da^{-0.6492}$	0.9308
May 18th–July 2nd	A	$gs = 4.748Da^{-0.5883}$	0.8298
	B	$gs = 4.3342Da^{-0.4062}$	0.5779
	C	$gs = 6.6674Da^{-0.5209}$	0.7971
	Dry-farming	$gs = 2.8276Da^{-0.6929}$	0.7840
July 3rd–August 29th	A	$gs = 5.9174Da^{-0.7842}$	0.8813
	B	$gs = 6.1129Da^{-0.6491}$	0.6505
	C	$gs = 5.4497Da^{-0.6863}$	0.8420
	Dry-farming	$gs = 2.8501Da^{-0.774}$	0.8698

Table 9 – Orchard productivity in kg tree^{-1} for 2004 dry-farmed year, and for the subsequent irrigation treatments A, B, and C of year 2006

Year	A	B	C	Dry-farming
	kg tree^{-1}			
2004		27.0 ± 5.10[a]		
2006	54.3 ± 6.3a	69.6 ± 16.9a	58.4 ± 8.4a	41.7 ± 2.3b

a Production in 2004 when the entire orchard was dry-farmed, prior to conversion to irrigation in 2005. Data are means of three replicate plots. The same letters in the line indicate that means are not statistically different ($P = 0.05$).

months, and the considerable rainfall in September 2006 gave average yields of 41.7 ± 2.3 kg tree^{-1}, considerably higher than the 27.0 ± 5.10 kg tree^{-1} harvested in 2004 and the 6.7 ± 1.5 kg tree^{-1} harvested in 2005, a dry and disappointing year for olive production.

4. Conclusions

The irrigation regime, and the summer and early autumn rains, differently affect the influence of water treatments on transpiration rates, soil water status and tree stomatal resistance. Excessive irrigation water was applied in the full-rate irrigation treatment. The SDI treatment, which received virtually the same amount of water as the full-rate irrigation treatment, maintained similar levels of transpiration rates but with no soil evaporation. The low average T/ET_0 ratios from June to August 2006 demonstrated by the full-rate irrigation and SDI treatments suggest that olive trees of cv. Cordovil slow down their physiological processes in the summer to improve their water use efficiency. Furthermore, during drought periods the daily transpiration rates of the RDI treatment above those supplied by irrigation reflect the propensity of olive trees to extract soil water from the large volume of soil around the trees, created by the 12 m by 12 m tree spacing. Trees from the dry-farmed treatment also benefited from the same mechanisms to extract water but by being not irrigated, they showed a much sharper decline in water stress coefficients than the RDI treatment. The fruit yield from RDI and dry-farmed treatments during 2006 contrasted to those found during the disappointing dry year of 2005 where there was more reduced fruit yield per tree, suggesting that RDI should be used for the irrigation of olive orchards in wet years with well distributed late summer rainfall and when from the onset of irrigation season farm water is in short supply. Otherwise, SDI appears to be the better option for scheduling irrigation of cv. Cordovil olives in Southern Portugal.

Acknowledgements

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