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Yield and olive oil characteristics of a low-density orchard (cv. Cordovil) subjected to different irrigation regimes

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ABSTRACT

The impact of different irrigation scheduling regimes on the quantity and quality of olive oil from a low-density olive grove in southern Portugal was assessed during the irrigation seasons of 2006 and 2007. Olive trees were subjected to one of the following treatments: A—full irrigation; B—sustained deficit irrigation (SDI) with 60% of ETc water applied with irrigation; C—regulated deficit irrigation (RDI) with irrigation water applied at three critical phases: before flowering, at the beginning of pit hardening and before crop harvesting and D—rain-fed treatment. Olive oil yield was significantly higher than rain-fed conditions in 2006, an "on year" of significant rainfall during summer. No significant yield differences were observed in the following "off year". Among the irrigated treatments, olive oil production of treatment B was 32.5% and 40.1% higher in 2006 and 2007, respectively than the fully irrigated treatment A, despite receiving 49% less irrigation water. Such strategy could allow for an efficient use of water in the region, of very limited available resources, and for modest but important oil yield increase. Nonetheless, on the "on year" of 2006 treatment C used 13.9% of the water applied to treatment B and produced only 23.9% less olive fruits which could also make it illegible as the next possible strategy to use for irrigating olive trees in the region, provided that water is secured latter in the summer, a period of vital importance for oil accumulation and very sensitive to water stress as the poor results of 2007 revealed. The different treatment water regimes did not impact on the chemical characteristics of olive oils that were within the set threshold limits. Similarly, the sensory characteristics of the olive oils as well as bitterness and pungency were negligible for all treatments allowing them to be assessed as of "superior quality".Overall, irrigation treatments had no influence on the commercial value of produced oils, being all classified as "extra virgin". Such funding may be of vital importance to farmers willing to further their irrigation area, save water and still retain the protected designation of origin (PDO) seal of quality for their oil.

1. Introduction

According to the International Olive Oil Council (IOOC) the world area devoted to olive-growing is 8.8 Mha (Carbot, 2007). This area is centered mainly in the Mediterranean basin, which has about 99% of the world's olive groves and produced in 2007/2008 around 2 030 800 metric tons of olive oil. In Europe, Portugal is the fourth largest olive oil producer, with 34 900 metric tons of olive oil produced in 2007/2008, mostly from its Southern Alentejo province where olive is a strategic crop providing for safe economic returns to farmers and jobs to entire rural communities.

According to the latest agricultural census (INE, 1999) the olive tree cultivation area in the southern province of Alentejo is around 148 402 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}. Due to the characteristically infrequent and limited annual rainfall of the region, there is a growing interest in improving the water use and oil content of those olive tree orchards through irrigation, if proven to be important in yield increases and better fruit quality. 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, making the region of Moura in Alentejo one of the five protected designation of origin (PDO) regions of Portugal.

Being olive-growing an integral part of the social fabric of the rural communities and one that provides safe economic returns to farmers, there is ambition among the olive growers to convert their traditional low-density olive groves into irrigation, a process that is

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Nomenclature

ET0	FAO-Penman-Monteith potential evapotranspiration (mm)
ETc	crop evapotranspiration (mm)
gs	stomatal conductance at midday (mol m^{-2} s^{-1})
K_{232}	UV absorbance (232 nm)
K_{270}	UV absorbance (270 nm)
R	actual soil water content in the root zone (mm)
R_{max}	soil water content at field capacity
R_{min}	minimum soil water content observed during the experiment (mm)
ψ_b	predawn leaf potential (MPa)
ψ_{min}	Midday leaf water potential (MPa)

already taking place. Also, with consumers demanding better quality olive oil and more perceptive about olive oil quality, the fine and distinct characteristics of those mono-variety oils from low-density autochthones cultivars are assuming a special relevance in the marketplace, as producers seek to find market niches for their low-producing but highly appreciated olive oil.

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. Yields are however low (Santos et al., 2007). To improve yields, compete with newly introduced and productive non-indigenous cultivars and preserve biodiversity and the character of the local oil, they are being converted to drip irrigation. Imposed often by the severe low water availability in the region, deficit irrigation management is being advocated as a way out to better yields, oil quality and economic returns of the irrigated orchards.

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 manage olive trees vary widely. The literature contains few results on the irrigation of traditional, low-density olive orchards. Lavee et al. (1990) 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 an 80 ha irrigated olive orchard compared to growth under rain-fed conditions. 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, suggesting that since recovery from water stress is rapid when irrigation is concentrated in the second half of the summer, this irrigation strategy 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 (SDI) or regulated deficit (RDI) irrigation 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. 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). The third phase of fruit development and oil accumulation, after pit hardening, is however very sensitive to water stress (Lavee and Wodner, 1991; Goldhamer et al., 1994; Moriana et al., 2003; Tognetti et al., 2005), being found to reduce fruit and oil production. Results and sensitivity of both SDI and RDI on low-density orchards also show that outcome vary considerably by genotype, summer rainfall and related local environmental conditions.

Water use strategies on irrigation of olive trees are often affected by changes in environmental water status, radiation and temperature that markedly impact on their seasonal physiological characteristics and oil. 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). A successful programme to irrigate low-density olive orchards seems to require and depend on knowledge of trees physiological responses and sensitivity to different irrigation strategies at different stages of their growth cycle. Also, according to Motilva et al. (2000), regimes of water stress may impact on oil characteristics and quality. Patumi et al. (1999) and d'Andria (2008) in studies conducted on Italian olive varieties concluded that applications of water in excess of 66% ETc during the whole season neither led to increases in production nor to better fruit quality, a clear indication of the benefits of deficit irrigation regimes. d'Andria et al. (2004) had shown that the production and quality of olive fruit of five studied cultivars benefited from deficit irrigation and had high yield when only 66% of ETc was supplied with irrigation. Grattan et al. (2006), in a study carried out on high-density olive trees of cv. Arbequina I-18 in California reported maximum productivity when 75% of ETc was supplied with irrigation. They argued that the best oil chemical quality is obtained from irrigation regimes supplying 33–40% of ETc water. Moriana et al. (2007) in a study conducted on low-density olive trees subjected to one of four treatments: rain-fed, 100% ETc, 125% ETc and a deficit irrigation treatment with 60 mm of water, obtained no significant statistical differences between treatments for fruit yield or oil production. However, Grattan et al. (2006) report that increases in yield due to irrigation water application can be largely offset by reductions in the percent of oil extracted. Concerning oil quality, Patumi et al. (1999, 2002) found fatty oils, acid composition, peroxide levels and shelf life not being affected by the amount of irrigation. Conversely, Gómez-Rico et al. (2005) report that oils of trees that undergo regulated deficit irrigation (RDI) regimes are of superior quality but similar in composition to ones under fully irrigated regimes. They argue that olive oil bitterness, spiciness and fruitiness are affected by irrigation, with a slight but more noticeable decrease in bitterness with increases in water application. Similarly, Muñoz-Cobo (2005) reports oils from highly irrigated olive trees been milder in sensory characteristics than counterpart oils from deficit irrigation regimes.

Definitive conclusions and consensus on the behaviour of yield and olive oil characteristics of low-density orchard subjected to different irrigation regimes are hard to establish, making the issue an on-going and debatable matter needing ever more site specific studies and research. Certainly, capturing the specific effects of regional and local climates, soils and indigenous olive trees genotypes on yields and oil quality under different irrigation regimes is of importance to all olive researchers and technicians. In southern Portugal it is of vital significance to farmers that owe their livelihood to olive oil trading and to entire rural communities tied up to jobs in olive orchard management as well on the being off of their farming community.

As seen, in order to apply a successful irrigation programme to olive trees it is of critical importance to have knowledge of their physiological responses and sensitivity to different irrigation strategies at different stages of their growth cycle. It is the aim of the present work to study those relationships and quantify yield and olive oil characteristics of low-density olive trees of cv. Cordovil grown in orchards in southern Portugal under full, sustained and regulated deficit irrigation management. The effect of soil and crop water status on olive tree physiological responses obtained via the plant water stress indicators stomatal conductance and predawn and midday leaf potential is evaluated at different stages of their growth cycle, to quantify leaf and plant water status and determine their sensitivity to different irrigation strategies. Concurrently, soil water status is evaluated through soil moisture profile probe sensors to account for the applied water and its accessibility by olive trees rooting system. Subjected to different irrigation schedules and amounts that might impact on oil quality, such is quantified by chemical and sensory analyses from extracted oils obtained from carefully harvested representative sub-treatments selected from each irrigation treatment.

2. Material and methods

2.1. Experiment location and design

This study was carried out in at the Herdade dos Lameirões near Safara, in the region of Moura, province of Alentejo, Portugal (lat. 38°05′15″N; long. 07°16′39″W; alt. 75 m) using a representative 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 in 2006 and 2007 from mid March to the end of October in 2006 and from mid March to the end of November in 2007 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 regulated deficit irrigation (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. Phenological stages of the olive trees was recorded throughout the irrigation cycle following the widely accepted BBCH decimal code and procedure described in Sanz-Cortés et al. (2002), a phenological descriptor of olive trees whereby the entire developmental cycle of the crop is subdivided into ten clearly recognizable and distinguishable longer lasting phases of principal and secondary growth stages. In the process, the pit hardening phase was identified and used to establish the onset of irrigation for treatment C, in July 3, 2006 and July 11, 2007, respectively.

Reference evapotranspiration, ET0 was calculated using the FAO-Penman-Monteith method and the procedures prescribed by Allen et al. (1998). Each tree was water supplied 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 meters 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).

The in situ soil classification indicates a clay soil (Vcx) until 0.40 m and silt loam transition to 0.45 m, underneath which a restrictive layer of very compact limestone and gravel elements limited root development and placement of soil moisture probes. Soil volumetric water content at field capacity (−0.03 MPa) was estimated as 0.36 $m^3 m^{-3}$ to 0.18 m, and 0.34 $m^3 m^{-3}$ between 0.18 and 0.50 m, whereas wilting point (−1.5 MPa) soil volumetric water content was 0.27 and 0.24 $m^3 m^{-3}$, respectively.

2.2. Soil water evaluation

Two representative trees per treatment were instrumented with access tubes for profile probe PR1 sensors (Delta T Devices, Lta., Cambridge, UK) at distances of 1, 2, 3 and 6 m along the tree rows and at depths of 0.10; 0.20; 0.30 and 0.45 m, below which the restrictive layer of limestone and gravel limited placement of access tubes and probes. One access tube was also installed between rows. Soil water content was monitored and recorded throughout 2006 and 2007 irrigation season, with results used to estimate the equivalent depth of water in the soil to 0.45 m, and its relative extractable water (REW) defined by Granier (1987) as:

$$\mathrm{REW} = \frac{(R - R_{\min})}{(R_{\max} - R_{\min})} \quad (1)$$

where R (mm) is the actual soil water content in the root zone; $R_{\min}$ (mm) the minimum soil water content observed during the experiment and $R_{\max}$ (mm), the soil water content at field capacity.

To complement the profile probe sensors readings and also guide the onset of irrigation, Watermark sensors (Irrometer Co. Inc., Riverside, USA) were placed inside the wet bulbs developed by the drip emitters at 1 and 3 m from the trunk and along the tree row, at 0.25; 0.45 and 0.65 m depths. Data were recorded via data logger and averaged on hourly intervals. When scheduled for each treatment, according to the full, RDI and SDI options and limits of water application, irrigation was applied to trees until reading on the Watermark sensor placed at 0.45 m depth approached the water potential of −0.06 to −0.07 MPa, a management decision that provided for the least number of weekly irrigation and helped to reduce losses via soil evaporation. Table 1 presents the amount of irrigation water applied to each treatment during 2006 and 2007. Data collected from an automatic meteorological station near the olive orchard provided for the inputs used on the calculation of Penman-Monteith potential evapotranspiration (ET0).

2.3. Plant water stress indicators

During 2006 and 2007 stomata conductance measurements were carried out in fully expanded leaves of the year of three trees per treatment, at sunrise and 13:30 GTM, well illuminated and at chest height. A diffusion of continuous flow LI-1600 porometer (LI-1600 Inc., IT USES) similar to the one described in Parkinson (1985) was used.

Predawn (ψ_b) and midday leaf potential ($\psi_{\min}$) were also evaluated to determine leaf and plant water status, according to the methodology described in Goldhamer and Salinas Fereres (2001). A pressure chamber type PMS (PMS Inst., Corvallis, OR, USES) was used and healthy leaves of the year in the shade and at chest height were monitored, after covering them with a wet cloth during the short period of time in-between incision and their placement in the pressure chamber. The ψ_b describes the plant water status when a balance between soil and tree water potential is deemed achieved Bergonci et al. (2000), while $\psi_{\min}$ provides critical tree water potential values when transpiration rates are at peak.

2.4. Sap flow measurement

The Compensation Heat-Pulse method (CHP) developed by Swanson and Whitfield (1981) and modified by Green et al. (2003) was used to evaluate tree sap flow and tree transpiration rates. As

Table 1
Fruit and oil yield (mean and standard deviation), water applied and water use efficiency for the different irrigation treatments.

Treatment	Yield production (kg/ha)		Oil yield (kg/ha)		Water applied (mm)		Water use efficiency (kg of oil/mm water)		Water use efficiency (kg of oil/mm water applied)	
	2006	2007	2006	2007	2006	2007	2006	2007	2006	2007
A	3741.3 ± 432.80ab[a]	504.5 ± 234.84a	652.6 ± 82.72ab	118.5 ± 57.13a	1307.6 (880.1)[b]	1045.8 (742.7)	0.50	0.08	0.74	0.12
B	4800.9 ± 1164.23a	783.5 ± 506.0a	966.3 ± 235.81a	197.9 ± 127.80a	876.3 (448.8)	681.9 (378.7)	1.10	0.23	2.15	0.42
C	4031.1 ± 576.42ab	165.6 ± 172.91a	735.7 ± 105.2ab	42.03 ± 43.62a	496.4 (62.5)	394.7 (91.5)	1.48	0.08	11.77	0.33
D	2875.0 ± 184.17b	108.9 ± 45.15a	564.0 ± 39.13b	30.7 ± 12.93a	427.5	303.2	1.32	0.07	–	–

[a] Treatments with the same letter in the same column are not significantly different by Tukey test at $P \leq 0.05$.
[b] The first value represents the total water applied (irrigation and rainfall) from the beginning of the vegetative development event to the harvest (in 2006 from March 5 to December 22 and in 2007 from March 10 to January 18); the value in-between parenthesis represents the total water applied by irrigation.

described in Fernández et al. (1996, 1997) a representative tree in each treatment was selected and outfitted with three set of heat-pulse velocity (HPV) probes and specific software was used for analysis of results. More detail on procedure is found in Santos et al. (2007).

2.5. Orchard yield, oil extraction and analyses

At harvest, olives from three representative sub-treatments in each irrigation treatment were hand picked and weighed. Concurrently, a sample of olives of about 3 kg per harvested sub-treatment were selected and transported to the laboratory for oil extraction. An Abencor analyzer (MC2, Ingenierias y System, Seville, Spain) system that reproduces industrial oil extraction (Grattan et al., 2006) was used for extraction of olive oil from the olive samples following the procedure and extraction phases described in Berenguer et al. (2006). The extracted oil was afterwards transferred to bottles of dark glass and stored at 4° C temperature while waiting for the chemical and sensory analyses.

Oil samples were analyzed for acidity (% of oleic acid), peroxide value (meq O_2 per kg of oil), UV absorbance (K_{232} and K_{270}) and sensory attributes of organoleptic evaluation, according to European Union Regulation EEC 2568/91 and European Union Regulation EC 1893/03 regulations. The ripeness index (RI) was evaluated following procedures described in Hermoso et al. (1999) by setting the maturity index scale from 0 (olives with intense green color) to 7 (olives with black skin and flesh purple to the pit). The percent of moisture in the resulting olive paste obtained from the Abencor extraction was estimated as moisture difference between wet and dry paste. The percent of oil content in the dry paste was evaluated by Nuclear Magnetic Resonance (NMS 110 minispect analyzer, Bruker) while the oil acidity, an indicator of free fatty acid levels in the oil, was expressed as percent of oleic acid (European Union Regulation EEC 2568/91 annex II). Free fat acid auto-oxidation plays an important role in the flavor characteristics and formation of organoleptic toxic compounds that reduce the nutritional value of the olive oil and its market value. Peroxide values were evaluated, as they indicate the state of initial oxidation of given oil and they are defined as the quantity of active oxygen (meq) in 1 kg of fat or oil (European Union Regulation EEC 2568/91 annex III). Secondary products resulting of oil oxidation where evaluated as UV absorbance, K_{232} and K_{270}, indices that indicate the state of oil conservation and secondary alterations induced by technological processes (European Union Regulation EEC 2568/91, annex IX).

Sensorial evaluation of the oil flavor was done by following the organoleptic method of classifying oil in a numerical scale of perception of the intensity of flavor stimulus in the mouth. It follows the present European Union Regulation EEC 2568/91 annex XII procedures where the intensity of the attribute is measured in a scale of 6, being 0 an imperceptible perception and 5, an extreme one. No negative attributes were observed. An overall grading procedure in a nine-point scale ranging from 1, the lowest quality, to 9, the exceptional quality, was lastly applied to attribute a single classification score to each oil simple analyzed. This final average score results from blending the quality attributes and weaknesses of the analyzed oil, allowing it to be classified as extra virgin when the overall grading is equal to or higher than 6.5, as virgin if graded 5.5–6.5, or lampant, if classified between 3.5 and 5.5.

2.6. Statistical analysis

The software SPSS version 15 was used for statistical data analysis. When a significant effect of factors in the study or the interaction between them is supported by the analysis of variance, the Tukey test with a level of signification $\alpha = 0.05$ was used for identification of differences between mean values. The experimental effect of the two trial years was separately analyzed.

3. Results and discussion

3.1. Climatic characterization

For the period in study the average total rainfall was 521.8 and 333.7 mm in 2006 and 2007 respectively, with the wet season spanning from October to April and a long and dry summer season lasting from May to September. Worthwhile noticing the impact of 2007 low rainfall on yield and produced oil. The dry season is the period for irrigation when trees need water to balance the high evapotranspiration rates resulting from the long and dry days, of intense net radiation (Fig. 1a and b), high vapour pressure deficit and low soil moisture content. Daily atmospheric water demand is high during the period, with potential evapotranspiration (ET0) rates reaching values as high as 8 mm day^{-1} in the months of July and August (Fig. 1a and b), and the stored winter rainfall in the soil is unavailable for remobilization, being long used during the dry spells of early Spring (Santos et al., 2007).

3.2. Soil water dynamics

Seasonal evolution of relative extractable water (REW) in the soil during 2006 and 2007 irrigation periods is presented in Fig. 2. With REW values for treatment A between 0.89 and 0.98 throughout the 2006 irrigation season (Fig. 2a) indicating well-watered trees, predawn leaf water potential readings, ψ_b were kept high, of less or equal −1 MPa (Fig. 3a), a threshold value for plant water stress according to Muñoz-Cobo (2005). Concerning treatment B, REW were at all times in-between 0.74 and 0.92, slightly lower than the values recorded for treatment A, as only 60% of tree evapotranspiration (ETc) was been replaced by irrigation.

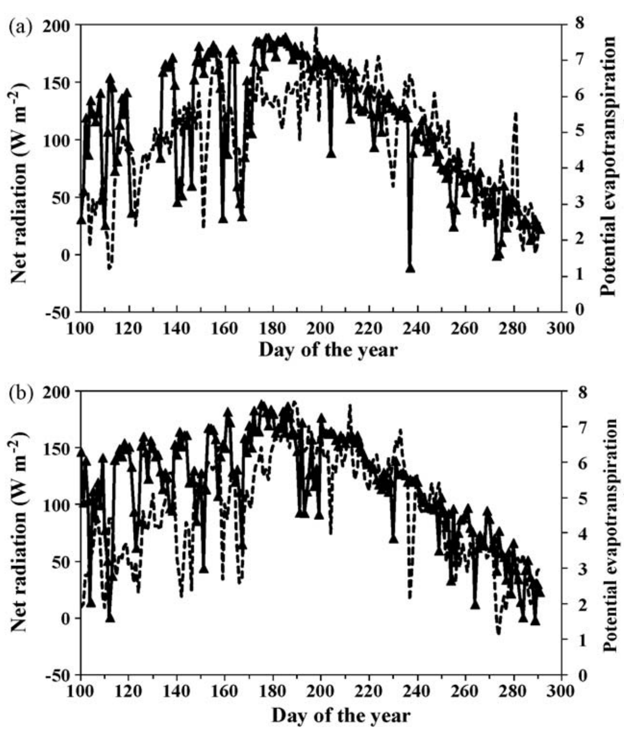

Fig. 1. Potential evapotranspiration calculated following Penman-Monteith equation and values from class A pan evaporation measured in a meteorological station located near at the experiment site and net radiation measured above the canopy throughout 2006 (a) and 2007 (b). ▲ net radiation; ----- potential evapotranspiration.

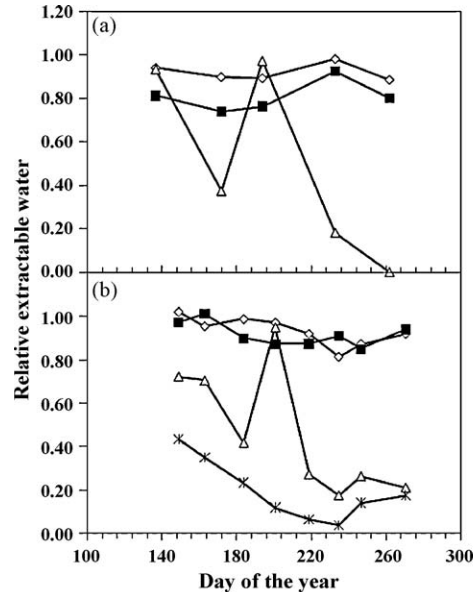

Fig. 2. Relative extractable water under treatments A, B, C and D. Estimating were made during the irrigation season of 2006 (a) and 2007(b). ◇, treatment A; ■, treatment B; Δ, treatment C; ⩙, treatment D.

Predawn leaf water potential readings reflected such fact with values slightly below −1 MPa. The regulated deficit irrigation regime imposed to treatment C, with water applied at periods more sensitive to water deficit (before flowering, at pit hardening and about 15 days before harvest), justifies the erratic behaviour of REW presented in Fig. 2a. Until the day of year (DOY) 172, a period without irrigation, REW gradually decreased to values close to 0.37. Following irrigation in DOY 194, REW climbed to a maximum of 0.97, when soil water content was 0.34 m^3 m^{-3} but after DOY 194 they gradually declined to their lowest value in DOY 262, when volumetric soil water content was of 0.11 m^3 m^{-3}.

During the 2007 irrigation season, treatment A presented values of REW in-between 0.87 and 1.0, except around DOY 235 when they dipped lower due to a week failure in the irrigation system. Fig. 2b presents such results. With 40% less water applied to treatment B, the REW values stayed in-between 0.85 and 1.0 and

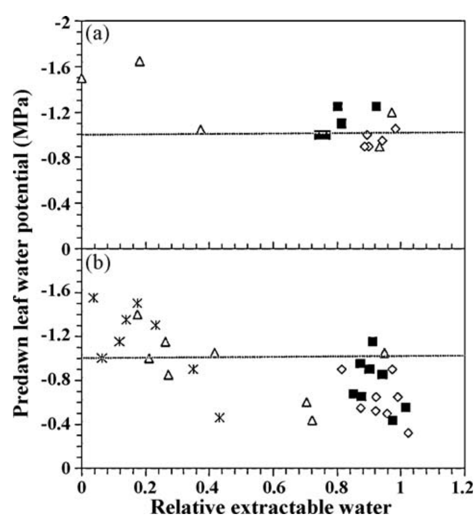

Fig. 3. Relationship between relative extractable water and predawn leaf water potential under treatments A, B, C and D in the experimental olive orchard during 2006 (a) and 2007 (b). Dotted line represents the predawn value, considered the threshold value for plant water stress. ◇, treatment A; ■, treatment B; Δ, treatment C; ⩙, treatment D.

close to the ones observed for treatment A, indicating that soil water stayed near field capacity. Predawn leaf water potential, ψ_b were slightly lower than −1 MPa (Fig. 3b), also indicating that well irrigated trees. For treatment C and during half of the period in evaluation, volumetric soil water content stayed low, of around 0.18 $m^3 m^{-3}$ with REW values alternating in-between 0.17 and 0.27. The former was recorded in mid August (DOY 235) when most of the soil moisture had been depleted. After irrigation, in DOY 201, REW recovered to 0.95, as did happen in 2006 (Fig. 3b). In the eight days of measurements, treatment D volumetric soil water content was below wilting point and REW values stayed in-between 0.04 and 0.43. However, when the soil moisture was replenished with 20.8 mm of rainfall, REW values quickly bounced back, between DOY 247 and 271 (Fig. 2b). In general, REW values remained always below 0.4 in this treatment and ψ_b (Fig. 3b) also reflected such fact with low values of ψ_b recorded during the period. Higher moisture in the soil throughout the summer irrigation cycle and consequent high leaf water potential confirm the importance of irrigating olive trees in Alentejo, a Mediterranean region denied of meaningful summer rainfall and where olive trees are conditioned to thrive in shallow soils of restrictive layer that limit deep soil water storage and remobilization by roots.

3.3. Midday stomatal leaf conductance and midday leaf water potential

During the irrigation season of 2006 the evolution of midday leaf water potential (Ψ_{min}) readings (Fig. 4a) was distinct for trees receiving the full irrigation (treatment A) and trees submitted to partial water stress (treatments B and C). The larger differential was observed at beginning of September, on DOY 233, of around −0.60 and −1.05 MPa respectively, reflecting the effect of the lower soil water content of treatments B and C, respectively on leaf water status. Treatment A, as expected, was the one presenting the highest Ψ_{min} readings throughout the season. The deficit irrigation treatments B and C recorded Ψ_{min} values that remained very close to −2 MPa in the first three periods of measurements (DOY 137, 172 and 194) and not far from the readings of treatment A. However into the summer, they decreased in the fourth day of measurements (DOY 233) when readings were the lowest, of −2.85 and −3.3 MPa respectively for treatments B and C. On the third day of measurements, DOY 194, even though trees of treatment C were being supplied with irrigation water and the volumetric soil water was very close to field capacity, of about 0.34 $m^3 m^{-3}$, the recovery of Ψ_{min} was not complete and stayed slightly below the readings of treatment B.

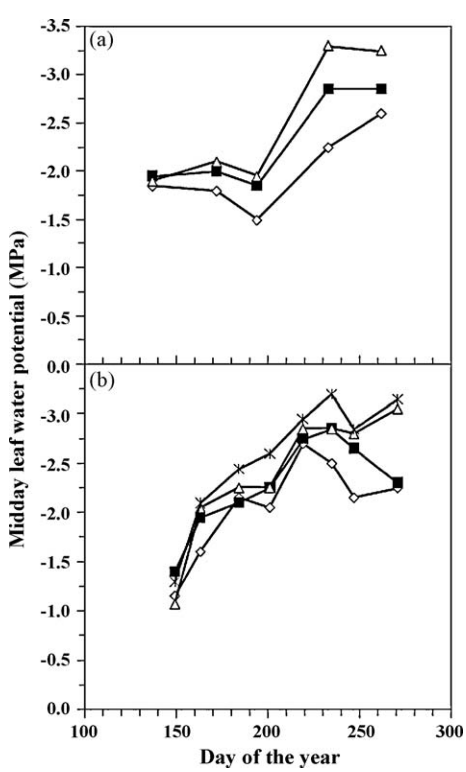

Fig. 4. Values of midday leaf water potential obtained with the pressure chamber in different days of 2006 (a) and 2007 (b). ◇, treatment A; ■, treatment B; Δ, treatment C; ⨯, treatment D.

In 2007 the status of leaf water was at its highest level for the different treatments on DOY 149 (Fig. 4b), coincident with the period under analysis in which volumetric soil water was at its highest for all treatments, except for treatment C. From DOY 149 onward they slowly declined for all treatments, as seen in Fig. 4b, due to non favorable summer net radiation which up to the fifth day of measurement, at DOY 219, presented high values of around 600 W m^{-2} (Fig. 6), to decline to values close to 500 W m^{-2} afterward. Vapour pressure deficit (VPD) was also high in the period, resulting that both variables were important factors influencing the transfer of water into the atmosphere and promoting the decline in Ψ_{min} readings. Overall, trees of fully irrigated treatment A presented the highest values of Ψ_{min}, closely followed by treatment B values. Here, Ψ_{min} values were at their lowest level on DOY 235, of −2.85 MPa. As for treatment C, in five of the eight days of measurement Ψ_{min} readings were lower than treatment B. Likewise in 2006, on DOY 219 and due to irrigation Ψ_{min} readings of treatment C showed slight recovery, but never a complete one, since Ψ_{min} remained quite apart from treatments A and B readings. It is conspicuous from Fig. 4 that for treatment C as the moisture content declined so did Ψ_{min}, with lower and lower values, up to −3.05 MPa in the end of the summer, on DOY 271.

The evolution of Ψ_{min} in 2006 and 2007 showing distinct differences among irrigation regimes confirm that the SDI regime of continuous water stress imposed by treatment B as more beneficial to trees than the regulated deficit regime of treatment C. In the latter, the irrigation scheduling applied to trees deprived them of needed water in crucial periods of the growing cycle, depicted by the progressive decline in their leaf potential values. Furthermore, with the imposed stress their recovery was slow and never fully achieved. For treatment D, Ψ_{min} readings quickly decreased from early mid June (−2 MPa) until DOY 235 when Ψ_{min} was the lowest, of around −3.2 MPa. Between DOY 235 and DOY 247 there was a slight recovery of Ψ_{min} readings with the replenishment of moisture to the soil resulting from the 17.5 mm rainfall (data not shown).

Midday stomatal leaf conductance (gs) was also influenced by the different irrigation regimes (Fig. 5). In 2006 (Fig. 5a), trees of treatment A presented the lowest levels of gs in the spring, on DOY 137, of about 0.079 mol $m^{-2} s^{-1}$. In this particular day, the volumetric soil water was however high, of 0.35 $m^3 m^{-3}$. The day was cloudy and net radiation at solar midday was of 431.2 W m^{-2} (Fig. 6). On DOY 194, gs again decreased noticeably, to 0.085 mol $m^{-2} s^{-1}$. With high water content in the soil, the decline in gs suggests stomata closure due to the relatively VPD, of around 5.53 kPa (Fig. 6). Connor (2005) mentioned decreasing stomatal conductance rates and low leaf water potential values reflecting leaf responses to adverse climatic variables and a mechanism to maintain transpiration efficiency. In the two last days of measurements (DOY 233 and DOY 262), gs values increased to value as high as 0.176 mol $m^{-2} s^{-1}$. In general, trees of treatment B showed a gs trend very similar to the one observed for treatment A but with slightly lower values. Concerning treatment C, on the first three days in which measurements were carried out (DOY

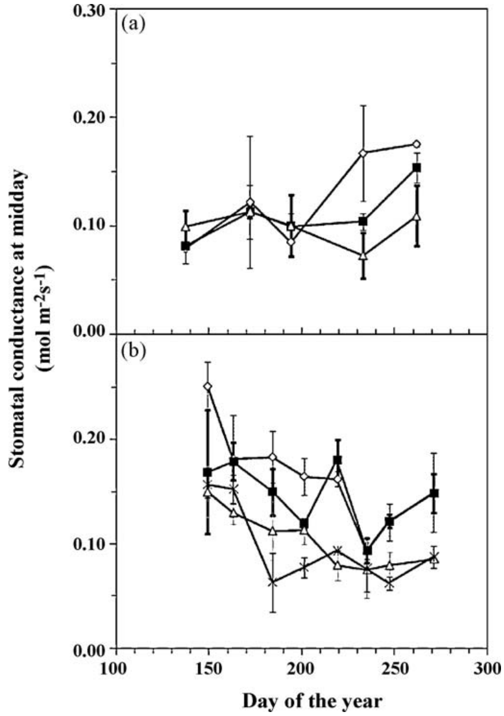

Fig. 5. Values of midday stomatal leaf conductance (gs) obtained with a porometer in different days of 2006 (a) and 2007 (b). Each point is the average of 3 measurements and vertical bars represent one standard deviation. ◇, treatment A; ■, treatment B; Δ, treatment C; ⋉, treatment D.

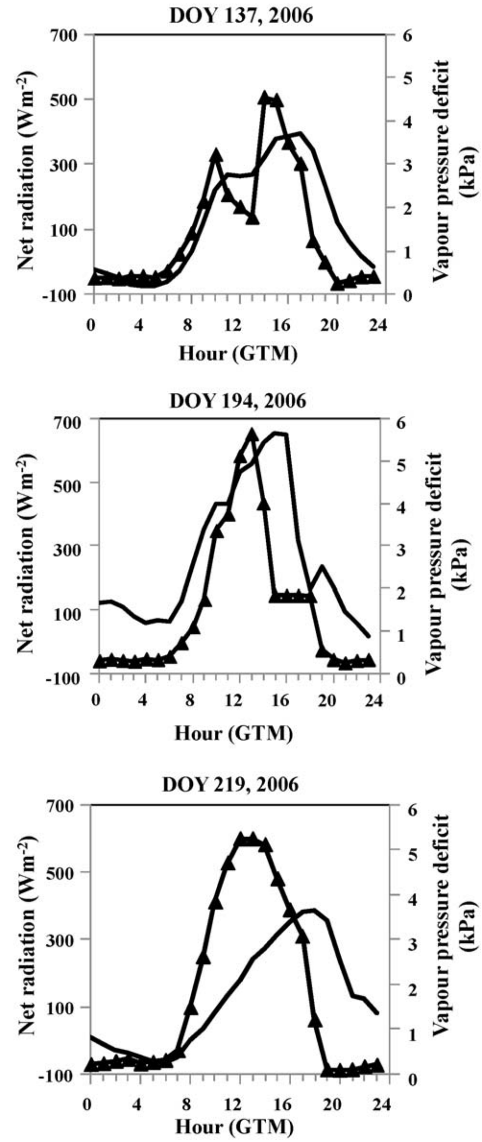

Fig. 6. Daily trend in net radiation and vapour pressure deficit in the experimental site on three different dates throughout the irrigation seasons of 2006 and 2007. ▲, net radiation; ———, vapour pressure deficit.

137 172 and 194), gs stayed close to 0.10 mol m^{-2} s^{-1}. On DOY 194, when trees were being irrigated gs values were still low, of about 0.101 mol m^2 s^{-1}, consequence of the previous days of water stress, and despite the already high soil water content, close to field capacity. Trees of treatment C presented on DOY 233 the lowest gs values, of around 0.073 mol m^{-2} s^{-1} when soil water content was low (0.155 m^3 m^{-3}), suggesting stomata closure due to the low soil moisture. By the end of the summer, DOY 262, the value of gs had increased only slightly.

The set of gs values obtained in 2007 (Fig. 5b) shows that leaves of treatment A recorded the largest gs value, 0.251 mol m^{-2} s^{-1}, in the spring, on DOY 149. Between DOY 163 and DOY 219, gs values had declined to 0.17 mol m^{-2} s^{-1}. On DOY 235 soil water content had decreased quite considerably and through the defensive mechanism stomata closure, gs readings of 0.094 mol m^{-2} s^{-1} were observed. From that day onward, there was a slight recovery in gs values, matching those of treatment B. In spite of the high water content in the soil, treatment A had only a partial departure from the observed low gs values in the last two days of measurement, when VPD and net radiation declined considerably by the end of summer. For treatment B, the highest gs reading was observed on DOY 219, of about 0.180 mol m^{-2} s^{-1}, and the lowest on DOY 235, as did observed in the same day for treatment A. Early into spring, on DOY 149, treatment C gs readings did present values close to those of treatment D, of about 0.157 mol m^{-2} s^{-1}. On DOY 201 the recorded values were close to those of treatment B, of 0.114 mol m^{-2} s^{-1} due to the added irrigation water, and on DOY 219 they were again very low and close to 0.080 mol m^{-2} s^{-1}. They remained low until the end of the summer. The evolution of Ψ_{min} and gs in 2006 and 2007 showing distinct differences among irrigation regimes confirm that the SDI regime of a constant deficit imposed to treatment B as more beneficial to trees than the regulated deficit regime of treatment C. In the latter, the applied irrigation scheduling and lack of late summer rainfall in 2007 deprived trees of needed water in crucial periods of the growing cycle, depicted by the progressive decline of leaf water potential and stomatal closure. Furthermore, with the imposed stress their recovery was slow and never fully achieved. Such fact agrees with Fernández et al. (1996) observation of delays in olive trees recovery after a period of severe water stress, probably due to xylem vessels cavitation. Moriana et al. (2003) also point out such delay in leaf water status recovery in olive trees. For treatment D, Ψ_{min} readings quickly decreased from early in the spring gs values of treatment D were high in the first two days of measurements (0.155 mol m^{-2} s^{-1}) but declined quickly throughout summer (0.062 mol m^{-2} s^{-1}) due to stomatal closure related to the ever decreasing level of moisture in the soil.

Both in 2006 and in 2007, Ψ_{min} and gs values of dry-farming treatment D were very low throughout summer, confirming that soil water profile was deprived of stored water for remobilization by the root system to fully complement trees water requirements. The results also corroborate the need to irrigate the traditional low-density olive trees in Alentejo, to alleviate summer water stress and help boost final yield.

3.4. Olive oil yield and characteristics

Table 1 indicates that olive yield varied considerably in the two years under study due to the effect of the biennial variation of fruit production that is a typical characteristic of this species. In 2006 "on year" of high yield, there were no significant differences in fruit yield between the irrigated treatments. Production varied between 4800.9 and 3741.3 kg ha^{-1}, with the higher and lower production rates assigned to between B and A respectively. Treatment C was the second most productive, showing a reduction in yield of 769.8 kg ha^{-1} when compared to treatment B. Fruit yield of treatment A, that had received the most water, was 1059.6 kg ha^{-1} less than treatment B. Even in the rain-fed conditions of treatment D yield were high, of 2875.0 kg ha^{-1}. In 2007 "off year" of poor harvest, there was no significant difference in fruit yield between irrigated and non-irrigated treatments. In general, yield suffered a severe decline when compared to 2006, of 86.5% and 83.7% for treatments A and B, respectively. Concerning treatments C and D, the decline was even more pronounced, of 95.9% and 96.2%, respectively. This fact suggests that trees under irrigation regimes that are particularly stressful to them, such as in the case of treatments C and D, suffer more drastic yield reductions in "off years". Deficit irrigation programmes such as the "regulated deficit irrigation" end up suffering more from a net accumulation of leaves and fewer flowers which tend to limit production in the subsequent year (Alegre et al., 2002). A similar widespread loss of production such as occurred in 2007 had been reported by Serrano (1998). They state that olive trees in "off years" are prone to yield drop as low as 90% of obtained in "on years". Sibbett (2002) discussed a range of possible factors that can lead to such phenomena including, among others, the level of irrigation and time of harvest. It is worth mentioning that nationally year 2007 was allegedly a "off year", with recorded average drop in olive tree yield of around 50% Anonymous (2007), jointly attributed to high temperatures that occurred in the ten first days of May, during flowering, immediately followed by days of very low and below average temperatures.

In 2006 the impact of irrigation treatments on olive oil yield per hectare was more evident than on fruit yield per hectare. Treatments B and D had the highest and lowest olive oil yield, of 966.3 and 564 kg ha^{-1}, respectively, in harmony with the results of Muñoz-Cobo (2005). Treatments A and C produced slightly higher olive oil yield per hectare than treatment D (Table 1). Even though there were no statistical differences in yield per hectare among irrigation treatments in 2006, treatment B yield was considerably higher than the other treatments. In 2007 it was once again the treatments B and D that produced the highest and lowest olive oil yield, again with no significant statistical differences among treatments. However, despite of the 2007 evident decrease in olive oil production compared to 2006, it is worth noticing that treatment B produced the highest olive oil yield per ha on both years while treatment D had the lowest yield. The 2006 reduction in fruit quantity between treatments B and A was of around 22.0% and, in-between treatments B and C it was around 16.0%, causing a reduction of olive oil for the same treatments of 32.5% and 23.9%, respectively. Similarly, in 2007 the drop in fruit and olive oil production between treatments B and A was of 35.6% and 40.1% respectively, and in-between treatments B and C of 78.9% and 78.8%. These results contrast with those obtained by Lavee et al. (2007) that in a test carried out in Israel reported average yield drop over a period of four consecutive years higher for fruit than for olive oil. Treatment B emerges as the one carrying the highest fruit and olive oil yield during the two years of trial. Using less 431.3 mm of water in 2006 than treatment A, it produced 313.7 kg per ha more olive oil and in 2007, despite the widespread drop in yield, it produced again more 79.4 kg of olive oil per ha than treatment A, using less 363.3 mm of irrigation water.

The percentage of fruit moisture during the extraction of the olive oil was higher in treatments receiving the highest rates of irrigation water (Table 4). Treatments A and D recorded the highest and lowest percentage of pulp moisture on both years under study. Compared to 2006, olive fruits from the different irrigation treatments presented a lower percent of moisture in 2007, probably due to the smaller amounts of water applied that year (Table 1). The difference in fruit moisture levels from treatments A and D was 8.8% and 16.5% in 2006 and 2007, respectively.

Concerning oil acidity, in 2006 treatment A that received the largest amount of water was the one that had the highest level of acidity (Table 2) of 0.77%, very close to the threshold value defined by European Regulation EC 1989/03 for extra virgin olive oil (<0.8%). All other treatments had lower acidity levels and the olive oil from treatment D had the lowest level, with 0.53% of acidity. There were no significant differences between treatments C and D, the ones with the lowest levels of acidity and also which received the lowest levels of irrigation water. In 2007 the behaviour was statistically identical to the 2006 results, with treatment A showing 0.73% of acidity, slightly higher than the other treatments. It is worth noticing that all treatments, with the exception of treatment A, showed a lower percentage of acidity in 2007, suggesting that the lower amount of water applied across all treatments (except A), could have been the reason for such a drop. The effects of irrigation on the acidity levels in olive oil are consistent with the results obtained by Berenguer et al. (2006). They found in a study carried out on cv. Arbequina over a 2 years period that olive oil from well-watered trees always had a higher percentage of acidity in the following year, despite reductions in water applications. Similarly, Muñoz-Cobo (2005) obtained higher levels of acidity in olive oil of well-watered olive trees. However, a different point of view is presented by Dettori et al. (1989) and Tovar et al. (2002) who conclude that olive oil acidity is not influenced by the amount of irrigation. Over the two-year study period olive oil from all irrigation treatments presented peroxide values which were below the official limit set by law, of 20 meq O_2 kg^{-1}. In 2006, peroxide count was higher in treatment D followed by treatments A and C. The lowest level was obtained for treatment B, as seen in Table 2. In 2007 the peroxide count of treatment B was still low, and the highest values were obtained for

Table 2
Quality index of cv. Cordovil olive oil obtained with the four irrigation treatments (mean ± standard deviation).

Oil analyses	Irrigation treatment	Crop season	
		2006	2007
Acid content (%)	A	0.767 ± 0.058a[a]	0.733 ± 0.058a
	B	0.667 ± 0.058ab	0.567 ± 0.058ab
	C	0.533 ± 0.058b	0.533 ± 0.058b
	D	0.533 ± 0.058b	0.50 ± 0.100b
Peroxide value (meq O_2 kg^{-1})	A	9.433 ± 0.115b	6.033 ± 0.153d
	B	6.600 ± 0.100c	6.933 ± 0.153c
	C	9.067 ± 0.058b	13.033 ± 0.153a
	D	10.267 ± 0.251a	10.000 ± 0.200b
K_{270}	A	0.144 ± 0.004c	0.123 ± 0.004b
	B	0.157 ± 0.004b	0.122 ± 0.004b
	C	0.177 ± 0.003a	0.156 ± 0.003a
	D	0.180 ± 0.004a	0.121 ± 0.004b
K_{232}	A	1.792 ± 0.004a	1.630 ± 0.030a
	B	1.838 ± 0.004a	1.549 ± 0.026ab
	C	1.789 ± 0.003a	1.620 ± 0.056a
	D	1.552 ± 0.004b	1.450 ± 0.05b

[a] Treatments with the same letter in the same column are not significantly different by Tukey test at $P \leq 0.05$.

treatments C and D. In general, over the two-year period the highest peroxide counts were recorded for olive oils of irrigation treatments C and D subjected to more water restrictions. In contrast, Salas et al. (1997) and Tovar et al. (2002) observed highest concentration of peroxides in well irrigated treatments, while Berenguer et al. (2006) obtained inconclusive results. Patumi et al. (1999) and Gómez-Rico et al. (2009) reported no relationship between irrigation water levels and peroxide counts.

Table 2 presents the UV absorbance values at 270 nm (K_{270}) obtained in 2006 and 2007. The highest values in 2006 were obtained in olive oils of treatments C and D that received the least amount of water and the lowest levels from well-watered trees (treatments A and B). In 2007 the highest values were obtained in olive oils from treatment C and no significant differences were observed between the others treatments. This observation is in agreement with the observation in Berenguer et al. (2006) that in years when all treatments receive less water, as in 2007, the statistics differences in the values of K_{270} between treatments are less marked. Tovar et al. (2002) and Gómez-Rico et al. (2009) found also no significant differences between irrigation treatments in respect to K_{270} absorbance levels. Concerning the UV absorbance at 232 nm (K_{232}), they were lower in the rain-fed treatment D, but presented no significant difference between the irrigated treatments (Table 2). These results contradict those of Muñoz-Cobo (2005), who obtained the highest K_{232} in olive oils produced in dry conditions. Both K_{232} and K_{270} absorbance levels for all treatments were however lower than the limits defined by legislation ($\leq$0.22–2.50 for K_{270} and K_{232}).

In terms of olive oil quality parameters, on both years (2006 and 2007) they were for all treatments within the limits established in the European Regulation EC 1989/03, allowing them to be classified as oils of high quality. Treatment B, which we had elected as the most favorable irrigation scheme to maximize olive yield, also produced the highest quality of olive oil. Generally known as having a slightly bitter and sharp flavor, the olive oils from cv. Cordovil obtained in our trial treatments in 2006 and 2007 (Table 3) were slightly bitter (0.5) or had no bitterness (0.0), mild, as preferred by Portuguese consumers. As for sharpness, they were slightly sharp (1) for the two years of the study. Oils from treatments C and D had a fruity flavor of 3, slightly better than treatments A and B that scored in level 2. However, the quality and flavor of the olive oils were greatly influenced by the ripeness index (RI), an indicator to be taken into account when producing oils of specific sensory and chemical characteristics.

The RI was only determined in 2007 on two different dates (Table 4). The first samples tested in November for RI showed no significant differences between treatments C and D. It showed that treatment A was maturing at a slower rate than the others and had a significantly lower level of RI, of 2.73. With the second sample taken a month latter, in December, olive from treatment D had the highest RI of 4.85 and no significant differences were observed between the irrigated treatments that had RI values of around 4. However, treatments A and B had the lowest rates of ripeness, probably due to the type of irrigation they were receiving. Worth pointing out that in-between the first and second sampling for ripeness, a rainfall of approximately 30.6 mm might have caused fruits of treatments C and D also to ripen at a slower rate (Grattan et al., 2006; Motilva et al., 2000).

Table 3
Sensorial attibutes of cv. Cordovil olive oil obtained with the four irrigation treatments.

Sensorial attributes	Treatment	Crop season	
		2006	2007
Fruity[a]	A	2	2
	B	2	2
	C	3	3
	D	3	3
Bitterness	A	0.5	0
	B	0.5	0
	C	0.5	0
	D	0.5	0
Pungency	A	1	1
	B	1	1
	C	1	1
	D	1	1
Overall grading[b]	A	7.5	7
	B	7.5	7.5
	C	8	7.5
	D	7.5	7.5

[a] Flavour description measured in a scale of 0–5 being 0 an imperceptible flavour and 5 extreme.
[b] Overall grading measured in a scale of nine points being 1 the lowest quality and 9 exceptional.

On a general assessment of the olive oils produced in 2006, treatment C oils scored with the highest organoleptic value of 8 (Table 3) on a scale of 1–9. However, all oils scored 7.5 points and above. In 2007, a year of less water applied to trees, the olive oils from treatments B, C and D had the highest organoleptic values of 7.5 and treatment A that received the most water, scored only 7. In general, all samples scored above 6.5 which according to European Regulation EC 1989/03 classify them as olive oils of superior quality and therefore "extra virgin".

3.5. Water productivity

Ranking the irrigated treatments in terms of oil yield per unit water, treatment C, despite the concentration of irrigation only in critical phases of growing cycle, had high water use efficiency in 2006, of 11.8 kg of oil per mm of applied water (Table 1). Treatment B was the second most productive, with 2.2 kg of oil per mm of water applied. The least productive treatment was treatment A which shows a clear decline in yield with the amount of water applied. In 2007, an "off year" of drastic reduction in yield, treatment B was the most productive with 0.42 kg of oil per mm of water applied, followed by treatment C. Treatment A trailed behind with 0.12 kg of oil per mm of applied water. It seems that in years of sharp reduction of water availability for irrigation, as in 2007,

Table 4
Influence of irrigation treatments on ripeness index, water content and oil extraction with the Abencor system in 2006 and 2007.

Treatment	Ripeness index		Water content (%)		Oil extraction-Abencor (%)	
	18-11-2007	27-12-2007	2006	2007	2006	2007
A	2.73 ± 0.271c[a]	4.14 ± 0.07b	53.21 ± 0.319a	45.99 ± 0.587a	17.41 ± 0.203d	23.34 ± 0.415c
B	3.24 ± 0.187b	4.27 ± 0.16b	49.42 ± 0.730b	36.71 ± 0.487c	18.25 ± 0.093c	25.26 ± 0.06b
C	3.65 ± 0.107a	4.39 ± 0.057b	47.18 ± 0.235c	40.03 ± 0.105b	19.61 ± 0.056b	25.33 ± 0.393b
D	3.57 ± 0.632a	4.85 ± 0.216a	44.37 ± 1.036d	29.47 ± 1.586d	20.12 ± 0.127a	28.17 ± 0.809a

[a] Treatments with the same letter in the same column are not significantly different by Tukey test at $P \leq 0.05$.

Table 5
Water supplied (irrigations and rainfall) and transpiration during 2006 and 2007.

Treatment	Rainfall (mm)[b]		Irrigation (mm)[a]		Total water applied in the period (mm)		Transpiration from sap flow (mm)	
	2006	2007	2006	2007	2006	2007	2006	2007
A	336.2	139.2	880.1	616.2	1216.3	755.4	764.3	690.8
B	336.2	139.2	448.8	314.2	785.0	453.4	789.7	736.4
C	336.2	139.2	68.9	67.8	405.1	207.0	848.2	666.4
D	292.9	139.2	0.0	0.0	292.9	139.2	446.5	349.7

[a] Water fraction (rainfall and irrigation) applied to the soil during the period from installation of sap flow sensors in trees: 2006, from March 2 to November 16, except for treatment D where sap flow sensors were installed in March 22.
[b] Water fraction (rainfall and irrigation) applied to the soil during the period from installation of sap flow sensors in trees: 2007, from March 29 to September 29. Total rainfall in 2006 was 521.8 and 333.7 mm in 2007.

treatment B is the best option for scheduling irrigation of olive trees of cv. Cordovil in southern Portugal.

Table 5 shows that during the period in which sap sensors were installed, the fraction of water applied to the soil both in terms of irrigation and rainfall that contributed to the production of biomass was different among the irrigation treatments. Trees of treatment A made the least use of applied water and had water productivity between 62.8% and 91.4% in 2006 and 2007, respectively. In 2006 about 37.2% of the water applied had been lost through evaporation or drainage and, in 2007 it was of 8.6% as the water applied had been reduced by 37.9% compared to 2006. Contrastingly, in 2007 trees of treatment B in addition of the water supplied by rainfall and irrigation, during the period of installation of sap flow sensors they also were able to harvest stored water from previous rainfall to provide for tree transpiration.

4. Conclusion

Results show that trees responded differently to summer rainfall and irrigation water. The sustained, SDI and regulated deficit irrigation, RDI scheduling regimes applied to treatments B and C respectively led to reduced applications of irrigation water and higher yield. However, over the two-year period the sustained deficit irrigation regime proved to be the most favorable irrigation strategy for use in the "on" and "off" years of olive oil production, leading to appreciable water resource savings and yields. Full irrigation of olive trees as assigned to treatment A led to waste of irrigation water, as olive trees from beginning of pit hardening until mid September slow down their vegetative growth and use less water despite of the amount applied. Results also support the hypothesis that irrigation of low-density olive orchards is needed as it increases yields and the amount of olive extracted oil. They also confirm that irrigation treatments has no influence on the commercial value of produced oils, being all of superior quality and classified as "extra virgin". Being the cultivar Cordovil highly appreciated for its high fruit free fatty acid and the fine sensory properties of its extracted oil, responsible for the seal of quality "Protected Designation of Origin (PDO)" conferred to the region, such findings are of vital importance to farmers for they allow them freedom to tackle the re-structuring and irrigation of their traditional low-density orchards confident of higher yields and fearless of losing quality and the PDO entitlement.

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