AGRICULTURAL WATER MANAGEMENT 87 (2007) 171–179

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Irrigation scheduling for traditional, low-density olive orchards: Water relations and influence on oil characteristics

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ARTICLE INFO

Article history:
Accepted 21 June 2006
Published on line 22 August 2006

Keywords:
Bitterness
Leaf conductance
Olea europaea
Regulated deficit irrigation
Stem water potential
Water relations

ABSTRACT

An experiment was performed in a low-density olive orchard (69 trees ha^{-1}) to study the recovery from water stress of olive trees under different irrigation managements. The effect of water stress on oil quality was also examined. The trees were subjected to one of four irrigation treatments: rain-fed conditions, irrigation with either 100% or 125% of the crop evapotranspiration (ET_c) level, or a deficit treatment in which only 60 mm of water were provided (at different times depending on the weather and phenological stage of the crop). The irrigation water in the deficit treatment was some 43% of the water applied in the 125% treatment. Plant water relations were determined periodically by measuring the water potential of covered leaves and the stomatal conductance at midday. The trees in the water deficit and rain-fed treatments rapidly recovered from water stress after receiving irrigation water or autumn rainwater, respectively, reaching the condition of the fully irrigated trees. However, stomatal conductance took longer to recover. Recovery at mid-summer in the deficit treatment was related to the amount of water in the soil; in autumn, however, this relationship was not so clear in rain-fed trees. The effect on oil quality was recorded in terms of the total concentration of phenolic compounds (TP). This was strongly related to the water stress integral, suggesting that the effect of irrigation on this variable occurs year-round and not just during the oil accumulation phase. Thus, even with low doses of water it should be possible to significantly reduce the TP concentration. Since recovery from water stress is rapid when irrigation is concentrated in the second half of summer, such an irrigation regimen might allow efficient use of the limited amounts of water available in central Spain.

1. Introduction

Olive oil is considered a healthy source of lipids, and this has led to an increase in its consumption. The high price this oil demands has encouraged growth in the amount of land devoted to olive production, and growers are showing increased interest in improving the productivity of their orchards. Irrigation is a vital factor in improving both

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doi:10.1016/j.agwat.2006.06.017

production and productivity (Moriana et al., 2003). However, in Spain (the world's foremost producer of olives and olive oil, where each region has its own traditional cultivar) olive orchards are traditionally rain-fed (Barranco, 1997). Since owners are very reluctant to uproot olive trees (even low yielding cultivars planted at extremely low densities), very traditional orchards are now being irrigated. However, increasing the irrigated area is very difficult in Spain as in the rest of the olive-growing world: water is frequently scarce and competition with non-agricultural users can be fierce (Fereres et al., 2003). The question therefore arises as to whether low-density olive orchards can truly improve their results with irrigation or whether this water should be put to better use.

The literature contains few reports on the irrigation of traditional, low-density olive orchards. Pastor et al. (1999) reported that in an 80 ha^{-1} olive orchard an increase in yield was obtained with irrigation compared to growth under rain-fed conditions, although no difference were seen between the irrigated treatments. Recently, a new model for calculating the crop coefficient (K_c) has been suggested for olive trees (Orgaz et al., 2006). In general, this new method specifies greater water needs than conventional calculations. However, in most parts of Spain, the legal irrigation limit for olive trees is between 100 and 200 mm—too little even for low-density orchards. Irrigation scheduling therefore needs to be carefully designed to optimise water use.

Regulated deficit irrigation (RDI) is commonly used with other fruit trees to reduce the amount of irrigation water applied without – or with only very small – reductions in yield (Behboudian and Mills, 1997). RDI imposes a period of water stress that is controlled in terms of its intensity and the moment of onset. In olive trees, the second phase of fruit development, when pit hardening occurs, is the most resistant to water deficit (Goldhamer, 1999) – which is when water provision under RDI irrigation can be halted – while the bloom is extremely sensitive (Moriana et al., 2003). The third phase of fruit development, oil accumulation, is difficult to pinpoint in the olive, but is also said to be sensitive to water stress (Lavee and Wodner, 1991). Tognetti et al. (2005) propose olive trees should receive RDI to cover 66% of crop evapotranspiration losses after pit hardening, although this treatment would not allow the complete recovery of the normal water potential and gas exchange rate. Even so, the olive is a drought resistant species, and severe water stress during pit hardening only slightly reduces fruit production (Goldhamer et al., 1994) and oil yield (Moriana et al., 2003).

The greatest profits to be made in the olive oil market are in countries that are not traditional consumers, e.g., Japan. These countries demand sweet oil. However, the most abundant cultivars in Spain in terms of area planted are "Picual" and "Cornicabra", from the south and the centre of the country, respectively (the major olive-producing regions of Spain). Both are considered "bitter" cultivars because their oil is rich in phenolic compounds (Uceda and Hermoso, 1997). "Sweet" varieties are therefore now in demand by oil companies, with which they hope to increase the quantities they sell to low consumption markets.

The bitterness of olive oil is influenced by the drought conditions suffered by the crop. Little information is available on the influence of RDI on oil characteristics. This type of scheduling has been reported to improve fruit quality in other trees (Behboudian and Mills, 1997). In olive trees, even when just 30% of the crop evapotranspiration (ET_c) is covered, a significant reduction in the concentration of phenolic compounds is seen compared to that obtained under rain-fed conditions for the cultivars Ascolana, Kalamata and Noceralla (Patumi et al., 1999). However, this is not the case of cvs. Leccino and Frantoio (Mangliulo et al., 2003). In cv. Arbequina, significant differences in oil phenolic content were reported between trees supplied water to cover 25% of the ET_c and those receiving water at all other ET_c rates, but not between 65%, 75% and 100% ET_c (Motilva et al., 2000). The effect may be different, however, in "bitter" cultivars. For example, in cv. Picual, Pastor et al. (2005) reported a wide variation in the concentration of phenolic compounds between years. Coverage of 47% of the calculated water needs during dry years led to a 50% reduction in the concentration of phenolic compounds with respect to rain-fed trees.

The aim of the present work was to establish the relationship between olive trees water status and oil characteristics in order to improve the irrigation schedules of low-density olive orchards. Since reduced quantities of water are available to olive orchards, the recovery from water stress was also studied in order to establish an appropriate irrigation schedule. A premise of this work was that these orchards should not receive the maximum amount of water possible in order to leave more for new orchards. The hypothesis tested was that small amounts of irrigation water can still improve the characteristics of the oil produced by traditional orchards, mainly by reducing the concentration of phenolic compounds and consequently the sensation of bitterness. The response of the trees to water stress and the recovery from deficit were therefore studied under different irrigation conditions.

2. Materials and methods

2.1. *Study and experimental design*

This study was undertaken between 2003 and 2004 in a 50-year-old olive (*Olea europaea* L. cv. 'Cornicabra') orchard in Almodovar del Campo, Ciudad Real, Spain (39°N, 3°W, altitude 640 m). The climate of the area is Mediterranean; the average annual rainfall is just 404 mm, mostly distributed outside of a 4-month summer drought period. The total rainfall was 426 and 484 mm during the 2003 and 2004 seasons, respectively, with 41 and 138 mm, respectively, from May to September (the irrigation season). Although the rainfall in 2004 was uncommonly high, both years experienced summer drought. ET_o was lower during 2004 than 2003 during the months of irrigation. Fig. 1 shows the rainfall and ET_o data for the experimental period.

The soil at the experimental orchard was a clay loam (depth 1.6 m). The upper limit (field capacity) of available water was 0.36 $cm^3\ cm^{-3}$, the lower limit (permanent wilting point) was 0.17 $cm^3\ cm^{-3}$. Tree spacing was 12 m × 12 m. Irrigation was provided 5 days per week by the drip method (eight emitters per tree; 4 $L\ h^{-1}$). The emitters were equally spaced around the tree 1 m from the main trunk. Pruning during the 2-year experimental period was limited to the main branches in order to obtain the maximum ground cover. The tree volume at the

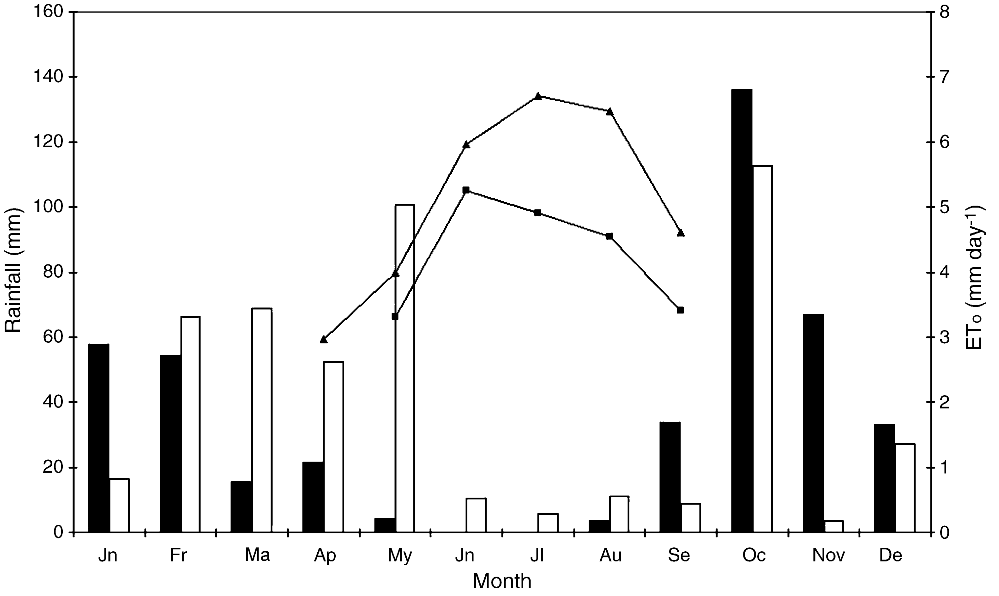

Fig. 1 – Rainfall and reference evapotranspiration (ET$_o$) for the 2 years of the experiment (2003: filled bar, ▲; 2004: empty bar, ■). ET$_o$ is presented only for the irrigation period. The crop coefficient (K_c) was variable: 0.6 in April and May, 0.55 in June, 0.5 in July and August and 0.6 in September.

beginning of the experiment was 49 and 74 m^3 per tree in the rain-fed and irrigated trees, respectively. The orchard was managed under no tillage conditions; weeds were controlled with post-emergence herbicides. A randomised complete-block design was used with four blocks of two trees that each received one of the following treatments:

(1) *Control*: Irrigation to supply the estimated crop evapotranspiration (ET$_c$), i.e., based on fully replenishing all soil water extracted.
(2) *125Control*: This treatment provided 25% more water than the Control. As described below, the ET$_c$ was estimated using the FAO method (Doorenbos and Pruitt, 1974) empirical crop coefficient values were therefore used with correction for canopy size. Since, the FAO method is less reliable in conditions of low ground cover, as in a low-density orchard, this treatment was used to determine the 'fully irrigated' conditions.
(3) *Deficit irrigation* (*DI*): This treatment wants to simulate the water management in a commercial orchard. Spanish irrigation regulations fix the amount of water that can be provided at 100 mm, but we decided to reduce to 60 mm. Some 60 mm of water were made available according to the weather and phenological stage of the trees. Irrigation was stopped when the autumn rains started, even though less than 60 mm had been applied. In 2003, a dry year, water was applied throughout the irrigation season with a distribution of 28 mm in May and June (full bloom and stage I of fruit development), 21 mm in July and August (stage II of fruit development), and 7 mm in September (the rains came early in this year). In 2004, a rainy year, water was applied from the beginning of August, when the stem water potential (Ψ) was around −3 MPa, at the same rate as that for the 125Control. In 2004, the total amount of water provided was 60 mm.
(4) Rain-fed conditions.

The amount of water provided was calculated by estimating the ET$_c$ using the FAO method (Doorenbos and Pruitt, 1974), and employing the crop coefficient (K_c) suggested for olive trees growing under the conditions reigning in Córdoba (Spain) (Fig. 1) (Orgaz and Fereres, 1997), with correction for the canopy size (Fereres and Goldhamer, 1990). The reference evapotranspiration, ET$_o$, was estimated using the Penman–Monteith equation employing daily data from a nearby automatic weather station. The DI schedule provided around 40% of the water provided to the Control trees in both years. Fig. 2 shows the distribution of irrigation for the 2003 and 2004 seasons. According to the ET$_o$ and rainfall values (Fig. 1), in 2003 the total irrigation provided to the 125Control (206 mm versus 154 mm) and Control (148 and 124 mm) trees was greater than in 2004. In both years, the DI treatment supplied around 60 mm (56 mm in 2003 and 60 mm in 2004), distributed more evenly over the season in 2003 but concentrated in August and September in 2004.

2.2. *Soil water measurements*

Soil water content was measured every 10 cm between the depths of 0.1 and 1 m every 2 weeks using a portable capacitance probe (Diviner 2000, Sentek Pty. Ltd., Stepney South, Australia) and employing the manufacturer's default calibration. The default calibration of this probe is based on combined data from a sand, sandy loam and organic potting soil (Sentek, 1999). Two 1.5 m-long access tubes were placed between two trees in each treatment plot in areas that were wetted and not wetted (different moisture zones) by the emitters. One access tube was placed near (around 5 cm) the emitters and the other at the mid-point between two trees. A weighted average based on the area of each moisture zone was

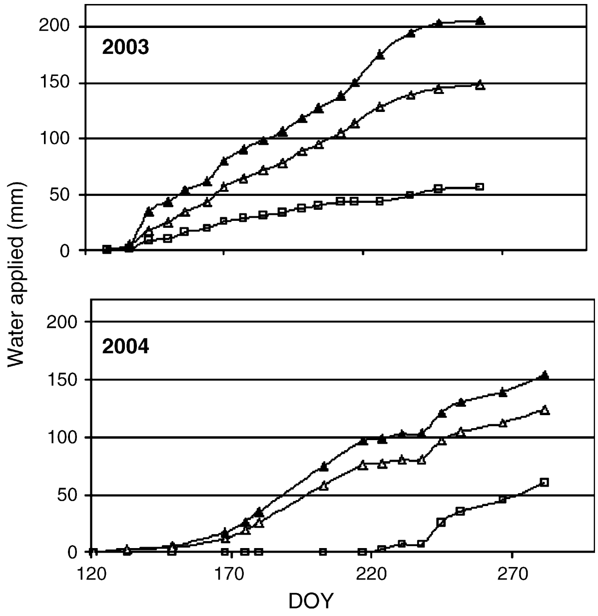

Fig. 2 – Seasonal variation in water provided during the experiment. ***Symbols*****: (▲) 125Control, (△) Control, (□) RDI.**

calculated to determine the soil water content. This measurement was only taken in 2004 season. In the absence of our own calibration no absolute values could be used. Therefore, the soil water content was described in terms of its change, i.e., the difference between consecutive measurements.

2.3. *Plant water relations*

Stem water potential (Ψ) measurements were used to evaluate the water status of the trees. Fully expanded leaves on branches near the main trunk were covered with aluminium foil for at least 1 h before removal at midday (13:00 h civil time). The water potential was then measured with a pressure chamber (Soil Moisture Equip., Santa Barbara, CA, U.S.A.). Stem water potential was measured periodically in one leaf per tree on one (2003 season) or two (2004) trees per replicate. In order to describe the effect of the different irrigation strategies, the water stress integral (S_ψ) (as defined by Myers (1988)) was calculated from the Ψ data in both years:

$$S_\psi = |\sum(\psi_m - c)n|$$

where Ψ_m is the average of stem water potential for any interval, c the value of the maximum stem water potential and n is the number of the days in the interval.

Abaxial leaf conductance (g) was measured with a steady-state porometer (Model LICOR-1600, Lincoln, NE, U.S.A.) between 12:00 and 14:00 h on three sun-exposed, fully expanded leaves per tree (the same trees in which stem water potential was measured).

2.4. *Fruit and oil yield*

All of the experimental trees were harvested during winter when the maturation index was around 4 (Hermoso et al., 1997). The individual fruit weight of each tree was measured and a sub-sample of 2 kg of fruits taken from each for oil determinations. Oil was extracted using the Abencor system (Mc2 Ingenieria y Sistemas, Seville, Spain), which emulates commercial oil extraction systems. Part of this oil was used for measuring the total concentration of phenolic compounds. Olive oil, to which 250 μL of a solution of an internal standard (15 mg/kg of syringic acid in methanol) were added, was dissolved in hexane (2.5 g in 6 mL), extracted by solid phase extraction (SPE) using a diol-bonded phase cartridge (Supelco Co., Bellefonte, PA), and analysed by RP-HPLC using a Spherisorb S3 ODS2 column (250 mm × 4.6 mm i.d., 5 μm particle size) (Waters Co., Milford, MA) with a mixture of water/acetic acid, methanol and acetonitrile as the mobile phase (Gómez-Alonso et al., 2002). Phenolic compounds were identified by comparison with reference samples and quantified at 280 nm using syringic acid as an internal standard, plus the response factors determined by Mateos et al. (2001).

2.5. *Statistical analysis*

The data were subjected to one-way ANOVA; means were compared using the Tukey test. Significance was set at $P < 0.05$. The number of samples measured is specified in the text and figures. Regression analysis was performed to determine the relationship between the concentration of phenolic compounds in the oil and the water stress integral.

3. Results

3.1. *Water relations*

Fig. 3 shows the change in midday stem water potential (Ψ) over the 2 years of the experiment. During the 2003 season, Ψ varied widely between treatments (Fig. 3). The rain-fed and DI treatments departed from Control values on day of year (DOY) 140, with the largest differences in mid-September. The minimum values, seen with the DI and rain-fed treatments, were below −4 MPa at the end of the irrigation season. The trees receiving the full irrigation treatments (Control and 125Control) showed a slight decrease in Ψ from mid June, although the minimum values were above −2 MPa throughout the season. No significant differences were seen between the Control and 125Control treatment or between the DI and rain-fed treatments. The Ψ of the rain-fed trees were significantly lower than that of the 125Control trees from DOY 170; the Ψ of the DI trees was significantly lower from DOY 198.

The changes in Ψ showed a similar tendency in 2004 (Fig. 3). The minimum value measured was around −4 MPa in the rain-fed treatment at DOY 282 (later than in the previous season). No significant differences were seen between the Control and 125Control trees in this year; minimum Ψ values were around −2 MPa. The differences between the rain-fed and the full irrigation treatments became apparent and significant from DOY 190 and after DOY 300, the trees recovered and no significant differences were observed with the Controls. The Ψ of the DI trees behaved differently than in the previous year due to the differences in irrigation management. Around DOY 203, the Ψ of the DI trees was significantly lower than those of the Control and 125Control trees.

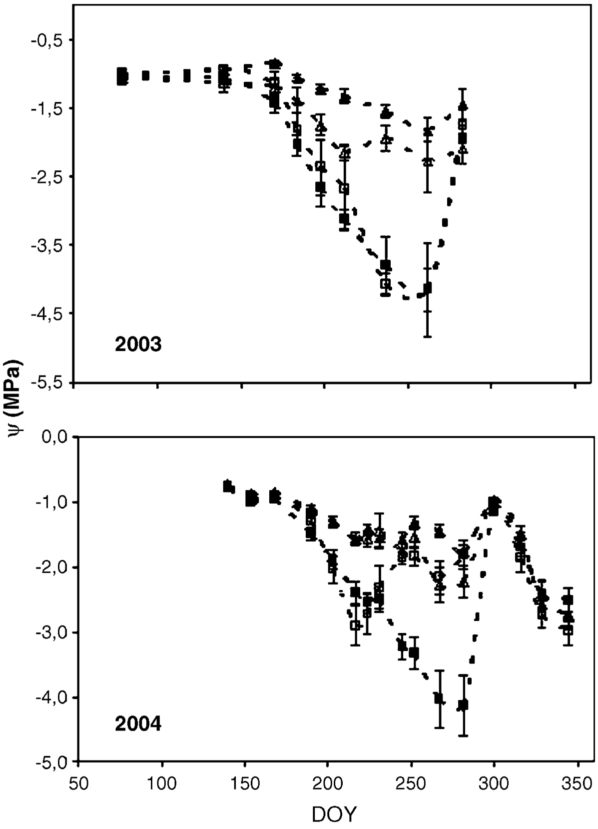

Fig. 3 – Change in midday stem water potential (*Ψ*) in 2003 and 2004. *Symbols*: (▲) 125Control, (△) Control, (■) rain-fed, (□) RDI. Each point represents the average of 4 (2003) or 8 (2004) measurements; the vertical bars represent the standard error.

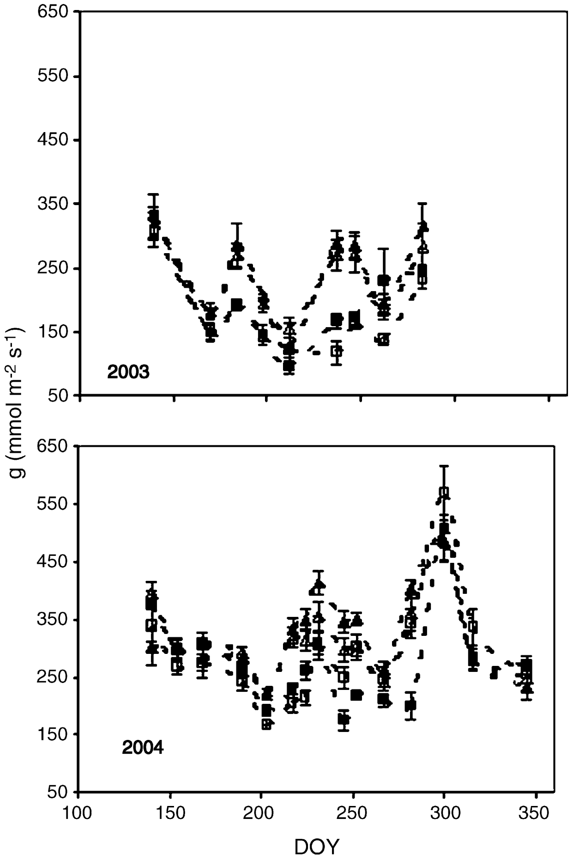

Fig. 4 – Change in midday stomatal leaf conductance (*g*) in 2003 and 2004. *Symbols*: (▲) 125Control, (△) Control, (■) rain-fed, (□) RDI. Each point represents the average of 12 (2003) or 24 (2004) measurements; the vertical bars represent the standard error.

However, irrigation was delayed until DOY 217 when the *Ψ* was around −3 MPa; until this time no significant differences were seen between the *Ψ* of the rain-fed and DI trees. Recovery started on this date in the DI treatment, according to the *Ψ* data, and was complete on around DOY 245 when no significant differences in *Ψ* were seen between the DI and Control or 125Control trees. The trees in all treatments showed a reduction in *Ψ* (with no significant differences) following the recovery that came with the autumn rains. This was probably related to the colder conditions.

Stomatal conductance was also affected by the irrigation treatment (Fig. 4). In the fully irrigated treatments (Control and 125Control), no significant differences between trees were found in terms of midday leaf conductance over the 2 years of the experiment. However, the values were lower in the 2003 season than in 2004 (Fig. 4). During 2003, the DI and rain-fed treatments also showed similar stomatal conductance rates, but lower than those observed for the fully irrigated trees. Significant differences were seen with respect to the fully irrigated Control from DOY 170. Minimum values were around 100 mmol m^{-2} s^{-1} in mid-summer, and though higher values were measured at the end of the season they were significantly lower than the Control and 125Control values.

In 2004, leaf conductance in the DI and rain-fed trees showed a similar trend until DOY 231, with significantly lower values than the Control and 125Control trees from DOY 203. However, when irrigation started in the DI treatment, leaf conductance increased until around DOY 252. No significant differences were seen between these trees and those of the Control and 125Control treatments from this date. In this year, the recovery of conductance values in the rain-fed trees, though later, was similar to that seen in the other treatments (no significant differences). The minimum leaf conductance values for this season were around 150 mmol m^{-2} s^{-1} at mid-summer in the rain-fed trees. Leaf conductance progressively increased from DOY 267 until DOY 300 in both the fully irrigated treatments.

Changes in soil water content (*θ*) were measured only in the 2004 season (Fig. 5). Similar values were found in all treatments until DOY 182, when the rain-fed trees showed significantly lower values than the Control and 125Control trees. The DI trees showed results similar to those recorded for the rain-fed trees, but significant differences were seen with respect to the two fully irrigated treatments from around DOY 203. The recovery of the soil water content in the DI treatment started with irrigation, but until DOY 252 it was not significantly greater than in the rain-fed treatment, and still lower than in the Control and 125Control treatments. Finally, from DOY 282, no significant differences were seen between

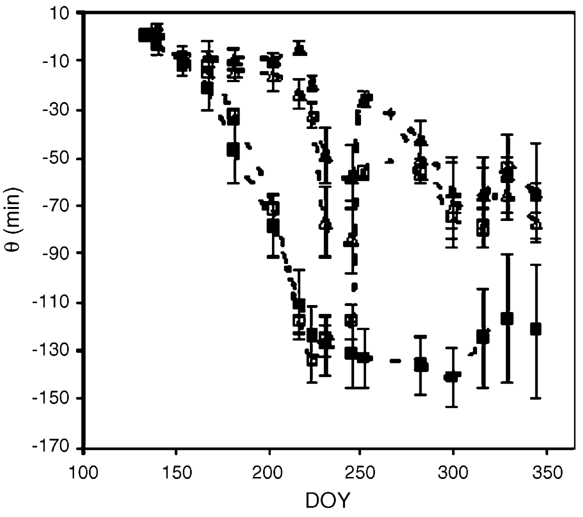

Fig. 5 – Changes in soil water content (θ) in 2004 at a depth of 1 m. The values are the cumulative differences between consecutive data. The upper limit (field capacity) of available water was 0.36 $cm^3 cm^{-3}$ and the lower limit (permanent wilting point) 0.17 $cm^3 cm^{-3}$. *Symbols*: (▲) 125Control, (△) Control, (■) rain-fed, (□) RDI. Each point represents the average of four measurements; the vertical bars represent the standard error.

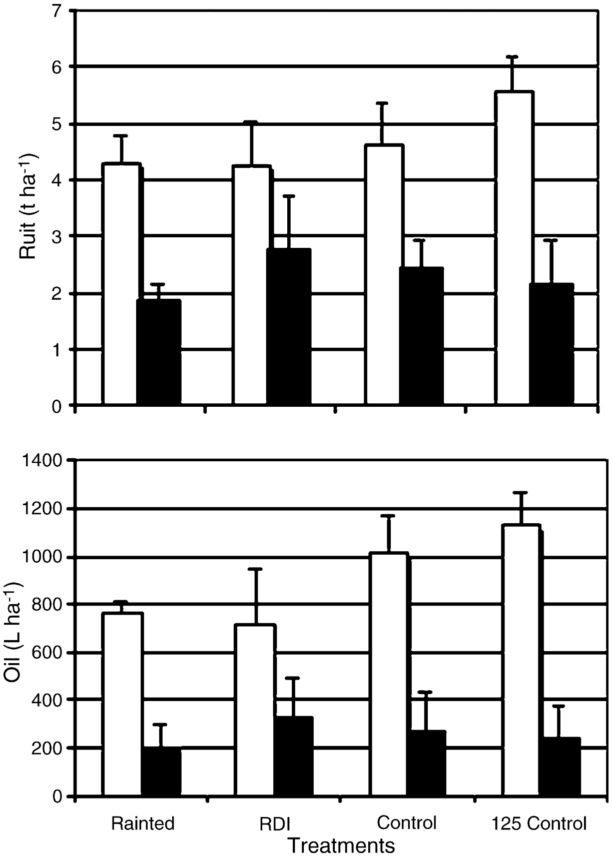

Fig. 6 – Fruit and oil yield in 2003 (□) and 2004 (■). Each histogram represents the average of eight trees; the vertical bars represent the standard error.

Table 1 – Total concentration of phenolic compounds in the oil in 2003 and 2004 (mg kg^{-1})

	125Control	Control	RDI	Rain-fed
2003	651 ± 124c	824 ± 56bc	1004 ± 160b	1364 ± 107a
2004	423 ± 102b	679 ± 19a	739 ± 51a	818 ± 224a

Values are the average and standard error. Different letters (a–c) indicate significant differences within the year ($P < 0.05$. Tukey test).

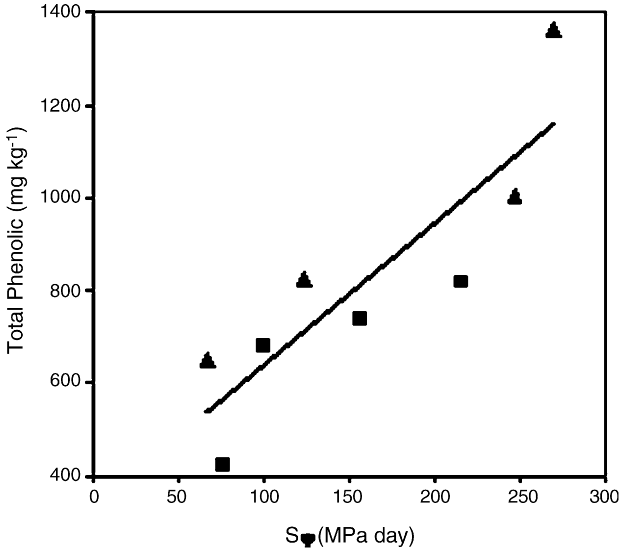

Fig. 7 – Relationship between the total concentration of phenolic compounds in the oil and the water stress integral (S_ψ) for 2003 (▲) and 2004 (■). The regression line represents the pooled data ($Y = 329 + 3X$; $n = 8$; $r^2 = 0.71^{***}$; RMSE = 149).

the irrigated treatments. The increase in the soil water content provided by the autumn rains was low.

3.2. *Fruit yield and oil characteristics*

The fruit yield showed the normal biannual pattern (Fig. 6). Fruit production in 2003, the "on" year, varied from 4 to 5.5 t ha^{-1}, with no significant differences between treatments. In the 2004 "off year" season, a reduction in fruit yield of around 50% of the "on" year value was seen, with the amounts collected varying between 2 and 2.5 t ha^{-1}, but again with no significant differences between treatments. The largest reductions in the "off" year were seen for the 125Control and rain-fed treatments, which showed values of 42% and 36% of those recorded in the "on" season. The Control and DI treatments suffered slightly smaller reductions to 51% and 64% of their "on" year levels, respectively.

Fig. 6 shows the oil yield obtained with the different treatments. No significant differences were seen between them, and the alternate bearing pattern was similar to that shown by fruit production. The largest decrease with respect to the "on" year was recorded for the 125Control treatment (20% of the "on year"); the rain-fed and Control treatments provided 30% of their "on" year yield while the DI trees supplied 45%.

Table 1 shows the TP values of the different oils at harvest. The highest were recorded in 2003. In this season, the rain-fed and 125Control trees produced oils that were significantly different in terms of TP concentration (1400 and 650 mg kg^{-1}, respectively). The values for the DI and Control treatment oils were between these levels. In 2004, the TP levels were lower, varying from 425 to 800 mg kg^{-1}. The TP value for the oil from the rain-fed trees was significantly higher than that of the 125Control trees in this season; the DI and Control tree oil TP levels were slightly lower than that of the rain-fed trees. A linear relationship was seen between TP and the water stress integral when the entire irrigation season was taken into account (Fig. 7). No improvement in this relationship was seen when the water stress integral was calculated from August (data not shown).

4. Discussion

The DI and rain-fed treatments led to the partial dehydration of the trees and the partial closure of their stomata. The stem water potential (Ψ) and leaf conductance values obtained were similar to those published for other olive orchards of low density or with small crown trees (Fernández et al., 1997; Pastor et al., 1999; Giorio et al., 1999; Alegre et al., 2002; Mangliulo et al., 2003; Tognetti et al., 2005), but higher than those described for denser orchards (Moriana et al., 2002, 2003).

Irrigation scheduling with small amounts of water or DI strategies implies a period of water stress. For the optimisation of its use, the recovery of tree water status should be rapid and should reach values similar to those of fully irrigated trees—or at least be significantly different to those of rain-fed trees. The present data confirm that olive trees have a high capacity to recover from water stress, as reported by other authors (Pastor et al., 1999; Goldhamer, 1999; Moriana et al., 2002, 2003). However, the delay between the full recovery of Ψ and that of leaf conductance may reduce the efficiency of irrigation. The results show that leaf conductance never fully recovered in the 2003 season in the DI and rain-fed trees, although in 2004 it recovered 1 week later than Ψ in the DI trees, and at the same time as Ψ in the rain-fed trees. The amount of irrigation water supplied by DI during 2004, and the rainfall (Figs. 1 and 2), were higher than in 2003. Therefore, the results suggest that larger amounts of water provided in a more concentrated fashion improve recovery from water stress. This agrees with that observed by other authors who report that severe water stress conditions lead to a lack of response in absorption when full irrigation is restarted; this is due to emboli in the roots preventing any significant xylem flow (Fernández et al., 2001). In addition, partial root drying experiments suggest leaf conductance is controlled by a signal from the roots (Giorio et al., 1999; Wahbi et al., 2005). This agrees with the slower recovery of leaf conductance compared to root hydraulic conductance in potted olive trees (Rieger, 1995). This conclusion is similar to that reached regarding the management of small amounts of water in DI. DI irrigation was more efficient when concentrated over short periods of time than when supplied over the entire season. The small amount of water applied during 2003 (Fig. 2) probably led to the roots growing into deeper soil horizons; indeed, the water status was not significantly different to that of rain-fed trees. However, when the same amount of water was applied at a higher rate (Fig. 2), the water status was significantly better than in the rain-fed trees.

Olive trees show high productivity with respect to water use (Goldhamer et al., 1994; Moriana et al., 2003). Although in the present work the irrigation treatments severely affected water relations in 2003 and 2004, the reduction in yield was not significant. Having just 2 years' worth of results (in fact just one because of the biannual cycle), and the high variability recorded in production (Fig. 6), limits the conclusions that can be drawn. Olive trees are traditionally considered to respond well to low amounts of irrigation water, yet no clear relationship between crop evapotranspiration and yield has always been described (Patumi et al., 1999; Pastor et al., 1999; Mangliulo et al., 2003). Dichio et al. (2003) report that the osmotic adjustment of olive trees leads to a large amount of water being extracted from the soil, which may reduce the effect of irrigation in low-density olive orchards. These low densities are those traditionally used in Spain, and are less productive than those used in other countries or indeed in new Spanish orchards (even in rain-fed conditions). Therefore, productivity with respect to water use is lower in low-density orchards than in higher density orchards.

The similarities in the alternate bearing patterns of fruit and oil (Fig. 6) may be related to the autumn recovery and the compensatory effect this has on fruit growth (Moriana et al., 2003). Differences in oil yield are usually associated with fruit production and not with oil production itself (Patumi et al., 1999; Moriana et al., 2003; Mangliulo et al., 2003), though the oil accumulation process has been described as sensitive to water stress (Lavee and Wodner, 1991). Indeed, several authors report differences in oil yield between irrigated and non-irrigated trees during dry years (Inglese et al., 1996; Pastor et al., 1999; Alegre et al., 2002) when rehydration is low or incomplete. Therefore, there are two critical phases when irrigation should be used to secure an adequate water status, around full bloom (Moriana et al., 2003) and again during oil accumulation. Under Mediterranean climatic conditions these phases commonly occur at the beginning and end of the rainy period, respectively.

The concentration of phenolic compounds was greatly affected by the water status of the trees, as reported by other authors (Inglese et al., 1996; Uceda and Hermoso, 1997; Patumi et al., 1999; Mangliulo et al., 2003; Pastor et al., 2005). The present data show that irrigation is important throughout the season and not just during the oil accumulation phase, since the TP concentration of the rain-fed trees was sharply reduced in 2004, which had a rainy spring (the last rain falling in June) and a dry autumn. Moreover, the DI treatment, which provided little water (around 30% of that provided in the 125Control treatment), led to significant reductions in TP concentration compared to the rain-fed treatment (not significantly different to the Control treatment). Patumi et al. (1999) reported a similar response in several cultivars receiving 33% ET_c irrigation, while Mangliulo et al. (2003) found no significant differences in yet other cultivars. Patumi et al. (1999) and Mangliulo et al. (2003) reported a reduction of the TP concentration in "sweet" cultivars of around 30% when the trees were fully irrigated (compared to rain-fed trees). In the present work, with ‘‘bitter’’ cultivars, a 50% reduction was seen, a similar percentage to that reported by Pastor et al. (2005). The changes in the DI irrigation scheduling during the oil accumulation phase did not produce a great reduction in the TP concentration compared to the previous year, but this result may have been influenced by the weather.

5. Conclusions

The results of this work show that irrigation in low-density olive orchards can be improved in two ways. Firstly, since irrigation is less effective in low-density orchards than in more dense orchards, small amounts of water should be used—but all should be provided over a short period of time. Provision of water during the critical periods of flowering and oil accumulation allows significant recovery compared to rain-fed trees—a lack of recovery from water stress will lead to a reduction in yield. Secondly, if small amounts of water are provided, the bitterness of the olive oil obtained will be reduced. This reduction of bitterness is unlikely to be related to the phenological stage of the tree, though further work is required to confirm this.

Acknowledgements

The authors thank Jesús Robles of the *Oficina Comarcal Agraria de Almodovar del Campo* for skilful technical assistance. This work was supported by project PBI03-015 of the *Consejería de Ciencia y Tecnología* of the *Junta de Comunidades de Castilla-La Mancha*.

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