

Effect of irrigation and tree density on vegetative growth, oil yield and water use efficiency in young olive orchard under arid conditions in Mendoza, Argentina

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Abstract We measured the effects of planting density (238, 317 and 476 trees ha⁻¹), irrigation (fully irrigated control vs. deficit irrigation) and their interaction on the vegetative growth, yield and irrigation water use efficiency (IWUE) of young olive trees during three seasons. In the water deficit treatment, irrigation was applied when midday stem water potential (SWP) dropped below -2.5 MPa; SWP of controls was maintained between -1.2 and -1.5 MPa. Across irrigation treatments, oil yield at high density (968 kg ha⁻¹) was 70 % higher than at low density. Reduction in oil yield due to deficit irrigation was not significant compared to control (501 vs. 664 kg ha⁻¹). IWUE at lower tree density averaged 1.5 kg ha⁻¹ mm⁻¹, increased by 50 % in intermediate density and by 57 % at the highest density. Deficit irrigation increased IWUE twofold with respect to controls. IWUE responded to the interaction density × irrigation whereby the highest IWUE (4.6 kg ha⁻¹ mm⁻¹) was obtained at highest density and deficit irrigation. IWUE was nonlinearly related to seasonal water stress integral ($S\psi$), where maximum efficiency corresponded to 180 MPa days. The negative correlation between fruit water concentration and $S\psi$ highlights the potential benefit of deficit irrigation of increasing oil extractability. The positive outcomes of increasing the density (higher oil yield) and deficit irrigation (higher IWUE,

lower water concentration in fruit) need to be weighed against the long-term effect on vegetative growth. Under our conditions, three seasons of water deficit reduced crown and trunk size by 35 % in relation to fully irrigated.

Introduction

In many olive growing regions of the world, including western Argentina, production systems are seeking higher yield and precocity, with technologies that combine drip irrigation, early production cultivars, trees formed to suit mechanical pruning and harvesting, and shifts in planting density from 100 trees ha⁻¹ in traditional orchards to high (200–600 trees ha⁻¹) or super-high plant density (1500–2500 trees ha⁻¹) (Connor 2006; de la Rosa et al. 2007). The greater production in the first years and the higher productivity may outweigh the higher costs of establishing intensive orchards (Feres et al. 2012). Additionally, the cost, availability and type of machinery for harvesting must be considered when choosing the distance between plants and rows, in addition to geometry and the final size of the canopy (Connor 2006).

In olive, the yield response to increasing tree density depends on environmental conditions, cultivar vigour and precociousness, orchard age and water regime. The direct correlation between fruit yield and tree density at early stages of grove development has been reported in olive (de la Rosa et al. 2007; Avidan et al. 2011). However, the early yield advantage of high-density orchards could decrease as the trees increase in size and competition for space, light, water and nutrients intensifies with time (Lavee et al. 2012).

Guerfel et al. (2010) found that a rain-fed 17-year-old olive orchard increased yield from 1.1 to 1.8 t ha⁻¹

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with a shift in density from 56 to 156 trees ha⁻¹. Under full irrigation, an adult olive orchard (50 years old) with 80 trees ha⁻¹ returned fruit yields in the range of 4.0–5.5 t ha⁻¹, while a 18-year-old orchard with 277 trees ha⁻¹ returned fruit yields of approximately 12 t ha⁻¹ (Moriana et al. 2003, 2007). Iniesta et al. (2009), in experiments performed on an olive orchard with 408 trees ha⁻¹, found fruit yields of 20 t ha⁻¹ in the seventh year after planting. In super-high plant density (1250–2500 trees ha⁻¹), cultivar-dependent yield ranged from 5 to 17 t ha⁻¹ in the sixth year after planting (de la Rosa et al. 2007; Avidan et al. 2011).

Increasing the planting density implies greater crop cover or higher proportion of solar radiation intercepted and less time from planting to maximum coverage. Both potential photosynthesis and transpiration are closely related to the proportion of radiation intercepted by the canopy (Green et al. 2003). Thus, it is necessary to consider the planting density in irrigation scheduling (Orgaz et al. 2006; Martínez-Cob and Faci 2010).

Fereres et al. (1981, 2012) included a reduction coefficient (K_r), which accounts for the fraction of soil covered by crops (GC), in the equation of water balance (Allen et al. 1998):

$$ET_c = ET_o \times K_c \times K_r \quad (1)$$

where ET_c is the actual crop evapotranspiration, ET_o is the reference evapotranspiration, and K_c is the crop coefficient; K_r is an empirical coefficient calculated as $2 \times GC/100$, with a limit of $K_r = 1$ for $GC > 50\%$ for almond trees in California (USA). The fraction of radiation intercepted at noon (f_{md}) has been used to scale K_c to specific growing conditions (e.g. Auzmendi et al. 2011; Girona et al. 2011; in apples and pears, Ayars et al. 2003; O'Connell et al. 2006 in peaches, Williams and Ayars 2005 in grapevines and Consoli et al. 2006 in oranges). The fraction of radiation intercepted at noon is more accurate than ground cover as it considers sun fleck and does not rely on the assumption of a circular projection of foliage on the soil surface underlying the calculation of K_r (Goodwin et al. 2006). However, f_{md} may not be representative of the size of the canopy when comparing different structures (Girona et al. 2011). The daily fraction of radiation could more accurately reflect the effect of tree height (Jackson 2003; Allen and Pereira 2009; Girona et al. 2011) and the adjacent rows (Oyarzun et al. 2007; Guillen-Climent et al. 2012).

In arid environments characterized by a limited and highly variable water supply (Noy-Meir 1973), the increase in intraspecific competition associated with the increase in tree density could set a limit on the yield potential of the individual plant. In this environment, it is therefore particularly important to quantify the interaction between tree density and water use. The aims of this study were to: (1) study the effects of irrigation, tree density and their interaction

on vegetative growth, oil yield and oil yield components in young, vigorous olives, (2) analyse the use of daily PAR intercepted as reduction coefficient for irrigation scheduling and (3) compare the irrigation water use efficiencies for oil production among planting models and irrigation levels.

Materials and methods

Site and orchard

The experiment was carried out during three consecutive seasons (2009–2010 to 2011–2012) in an olive (cv. Frantoio) orchard planted in 2004 at the experimental farm of INTA Junín (33°06'S, 68°29'W, 653 masl), in the arid environment of Mendoza, Argentina. The region has an average annual rainfall of 165 mm concentrated during the summer, average annual temperature of 15.8 °C and a frost-free period between October and April. The soil is a 4-m-deep clay loam (Typic entisol torrifluent, Abraham and Martínez 1996) with pH of 7.5. Planting densities were 238, 317 and 476 trees ha⁻¹ that were related to planting distance between trees (6.0, 4.5 and 3.0 m, respectively) while maintaining the distance between rows (7 m).

Irrigation treatments

Irrigation was supplied with a double-irrigation line spaced 1 m apart and 16, 12 and 8 emitters (each delivering 2 l h⁻¹) per tree for the 238, 317 and 476 trees ha⁻¹, respectively. The emitters were spaced at 0.75 m along the drip line. Irrigation frequency was the same for all treatments and varied from once per week in spring and autumn to twice per week during summer. Each plot had one valve to control the operating time according to tree density needs.

Two irrigation regimes were established: control and deficit irrigation. Controls received 100 % of the crop evapotranspiration (irrigation plus effective rain). Crop evapotranspiration was calculated with Eq. 1, using ET_o calculated with Penman–Monteith modified by FAO (Allen et al. 1998), $K_c = 0.70$ estimated for young olive trees by Girona et al. (2002) and K_r estimated as fraction daily of PAR intercepted (explained below). Deficit irrigation trees were irrigated when midday stem water potential (SWP) dropped below -2.5 MPa (Moriana et al. 2002). No attempt was made to use adjusted K_c and SWP threshold to plant density. The irrigation was 50 % of ET_c (using K_r corresponding to the plot) accumulating the week previous to SWP measurement. Irrigation ended when SWP was equal to or above -2.5 MPa. After the harvest, DI was irrigated with 100 % of ET_c estimated during the previous 15 days, in order to alleviate stress and to mitigate possible effects of low temperatures during winter (Pérez-López et al. 2010).

Measurements

Meteorological data

Daily meteorological data recorded at an automated weather station located 80 m from the experiment included maximum and minimum temperatures, relative humidity, rainfall, solar radiation, vapour pressure deficit and wind speed.

Daily fraction of intercepted solar radiation

The daily fraction of photosynthetic active radiation (PAR) intercepted by the orchard (f_D) was measured with a ceptometer (Cavadevice, Buenos Aires, Argentina). The measurements were made on sunny days in the area beneath the central trees of each plot, using a 1 m × 0.5 m grid within the space assigned to each tree (i.e. 84, 63 and 42 measurements per plant in 238, 317 and 476 trees ha⁻¹, respectively). The measurements were carried out every 2 h from sunrise to sunset. Within each plot, the ceptometer was placed perpendicular to the row direction in the shaded and non-shaded areas to capture measurements over the entire ground surface area of the plot. Immediately before the under-canopy measurements, we measured PAR at an open site with no interference from the canopy, approximately 1.5 m above ground level. Daily measurements were taken in September (i.e. the beginning of vegetative growth), January (i.e. the beginning of pit hardening and the end of vegetative growth) and April (i.e. before harvest). The f_D was calculated as a daily average of [100 × (1-mean PAR below the canopy/PAR outside the canopy)].

Stem water potential

Midday SWP was measured on sunny days between 11:30 and 12:30 h solar time at 1- to 2-week intervals using a Scholander-type pressure chamber (BioControl, Buenos Aires, Argentina). Two leaves per tree were sampled following the procedure outlined by McCutchan and Shackel (1992). Mature leaves near the trunk were enclosed in a small plastic bag covered with aluminium foil at least 90 min before measurements. The leaves were excised with a sharp blade and immediately placed with the bag inside the chamber. Seasonal (September–April) water stress integral ($S\psi$) was individually calculated for each plot according to Myers (1988):

$$S\psi = \sum_{i=0}^{i=t} |(\overline{\text{SWP}}_{i,j+1} - c)n| \quad (2)$$

where $\overline{\text{SWP}}_{i,j+1}$ is the average SWP for any interval $i, i + 1$; c is the maximum SWP (−0.62 MPa), and n is the number of days in the interval.

Vegetative growth, oil yield and its components

To determine the crown volume, the shape of the canopy was assumed to be ellipsoid with one vertical and two horizontal (in the direction and perpendicular of the row) diameters. The trunk perimeter was measured at 30 cm from the ground. The crown volume and trunk perimeter were measured concurrently with daily PAR intercepted.

The trees (in which SWP was monitored) were manually harvested on 12 April 2010, 27 April 2011 and 9 April 2012. From a 2-kg sample, 100 fruits were weighed to determine their average weight. The maturity index was determined by classifying 100 fruits from 0 to 7, according to skin and pulp colour (Beltrán et al. 2004). The total number of fruits from each tree was estimated from the average fruit weight and the harvest weight. Thirty fruits were used to determine fruit oil concentration and 50 fruits to determine the pulp/pit ratio. Alternate bearing index (ABI) was calculated as:

$$\text{ABI} = \left[\frac{1}{n-1} \right] \left[\frac{|a_2 - a_1|}{a_2 + a_1} + \frac{|a_3 - a_2|}{a_3 + a_2} \right] \quad (3)$$

where n is the number of years of evaluation; a_1, a_2 and a_3 are fruit yield for a determined year.

Oil concentration was measured using the method of Avidan et al. (1999). Briefly, 5 g pulp samples were dried over 48 h at 60 °C. The dried pulp was macerated in 15 ml of petroleum ether (60°–80°) and shaken for 12 h in darkness. Then, the samples were filtered and transferred into previously weighted tubes. During the filtering process, tubes and filter paper were washed with 5 ml of petroleum ether. The tubes were held at 60 °C until they reached constant weight. Oil concentration was estimated as the quotient, in percentage, of oil weight and pulp weight on a dry (OC_{DP}) basis. A subsample of ten fruits was weighted and dried at 60 °C until it reached a constant weight in order to estimate water concentration as 100 × (fresh wt – dry wt)/fresh wt. Oil yield (kg oil tree⁻¹) was calculated as:

$$\text{Oil yield} = (\text{FFY}) \times (P/F) \times (\text{DW/FW}) \times \text{OC}_{\text{DP}} \quad (4)$$

where FFY is fruit fresh yield, P/F is pulp/fruit fresh weight ratio, DW/FW is the relation between dry and fresh fruit weight, and OC_{DP} is pulp oil concentration on a dry weight basis. Irrigation water use efficiency (IWUE) was calculated as the ratio of fruit yield and irrigation (IWUE_F) or oil yield and irrigation (IWUE_O).

Experimental design and statistics

The factorial combination of two irrigation levels and three tree densities was arranged in a completely randomized design block (by crown volume) with four replicates. At the start of the study, the canopy volume did not differ among tree densities and irrigation treatments. The experimental plots were 3 rows \times 5 trees where the central tree of the central row was used for collecting data. This design (two trees as buffers, located at both sides of the measurement unit) aimed to reduce border effects due to irrigation treatments of adjacent plot. ANOVA was used to test for the effect of plant density, irrigation and their interaction on response variables, and means were separated using the LSD-test. Regression analysis was applied to study the relationships between oil yield and its components and seasonal water stress integral.

Results

Seasonal conditions

Weather conditions are summarized in Table 1. Rainfall was close to the long-term average in 2011–2012, below average in 2009–2010 and above average in 2010–2011. As usual in Mendoza, rainfall concentrated between December and May and was only a small fraction of reference evapotranspiration (Table 1). In irrigation scheduling, the effective rainfall (Table 2) was considered when daily rainfall was equal or higher than 12 mm, and then effective rainfall was estimated daily as (daily rainfall – 12 mm) \times 0.80 (Puertas 2009). Monthly mean temperatures from September to March in 2009–2010 and 2011–2012 were higher than in 2010–2011 (20.7 vs. 19.6 °C, respectively); April was slightly cooler in 2009–2010 than in the other two seasons (14.1 and 15.4 °C, respectively).

Stem water potential

Figure 1 shows the seasonal evolution of midday SWP. No significant density \times irrigation interaction for SWP was detected, and thus, main effects were analysed individually. The SWP was largely unaffected by tree density. However, in fully irrigated controls, trees at the lowest density occasionally had higher SWP. By contrast, the SWP under deficit irrigation tended to decrease with increased density. On the other hand, SWP differences between control and deficit irrigation decreased as the experiment progressed in lowest density treatment, while differences tended to be maintained in the medium and high densities (Fig. 1).

The SWP was highly responsive to irrigation regime (Fig. 1, top panel). In control trees, average SWP weighted by number of days between measurements from September to December (begin pit hardening) was -1.3 ± 0.02 and from January to April (harvest) was -1.5 ± 0.02 , irrespective of tree density and seasonal conditions. Under deficit irrigation, the pattern of SWP varied among seasons. In 2009–2010 and 2011–2012, SWP declined sharply from the beginning of the experiment, reached a minimum at the beginning of January and remained low at around -2.25 MPa until harvest. However, in 2010–2011, SWP declined sharply during spring, but above-average rain from December to March rehydrated trees in the water deficit treatment, hence increasing the SWP. Nonetheless, SWP under deficit irrigation was significantly lower than in controls. Average SWP under deficit irrigation was -1.6 ± 0.04 before and -2.0 ± 0.06 MPa after pit hardening.

Water applied

Water applied through irrigation revealed a significant interaction between planting density and irrigation regime (Table 2). This interaction reflected the increase in water

Table 1 Monthly mean temperature, rainfall and reference evapotranspiration during three growing seasons at Mendoza, Argentina

Month	Temperature (°C)			Rainfall (mm)			ET _o (mm)		
	2009–2010	2010–2011	2011–2012	2009–2010	2010–2011	2011–2012	2009–2010	2010–2011	2011–2012
September	11.2	13.0	14.5	4	4	0	110	111	128
October	17.5	17.1	16.7	0	6	20	160	156	155
November	21.2	19.8	21.0	0	10	61	197	181	169
December	22.9	23.0	24.1	46	48	1	209	224	191
January	25.2	23.6	25.4	18	58	19	228	206	182
February	23.3	21.7	23.4	5	61	26	158	152	173
March	21.9	19.2	20.9	27	27	0	141	131	137
April	14.1	15.5	15.2	1	2	30	83	96	84
Total				102	217	157	1286	1257	1219

Table 2 Applied water, effective annual rainfall (ER) and irrigation water use efficiency for olive fruit yield (IWUE_f) and oil yield (IWUE_o) in a trial combining three planting densities (trees ha⁻¹) and two irrigation regimes (fully irrigated, CT and water deficit, DI) during three growing seasons in Mendoza, Argentina

Source of variation	Applied water (mm)	ER (mm)	IWUE _f (kg ha ⁻¹ mm ⁻¹)	IWUE _o (kg ha ⁻¹ mm ⁻¹)
Density × irrigation				
476 × CT	428		13.9	2.3
317 × CT	289		8.1	1.4
238 × CT	219		8.2	1.5
476 × DI	83		26.9	4.6
317 × DI	70		24.3	4.6
238 × DI	68		8.8	1.5
Density				
476	255		19.8	3.3
317	179		16.2	3.0
238	144		8.5	1.5
Irrigation				
CT	312		10.1	1.7
DI	73		19.6	3.5
Season				
2009–2010	204	15.4	11.1	1.9
2010–2011	168	75.3	13.1	2.3
2011–2012	206	46.7	20.4	3.6
LSD (0.05)				
LSD _{Density}	22.1	–	8.18	1.38
LSD _{Irrigation}	18.1	–	6.67	1.12
LSD _{Season}	22.1	–	8.18	1.38
LSD _{D×I}	31.3	–	11.57	1.95

The least significant difference (LSD) is presented when ANOVA indicated significant effect ($P < 0.05$)
ns no significant ($P < 0.05$)

supply with increasing density in fully irrigated controls, while water supply did not change with planting density under deficit irrigation. In controls (across the seasons), 476 trees ha⁻¹ used 29 and 44 % more water (irrigation plus effective annual rainfall) than 317 and 238 trees ha⁻¹, respectively. In controls, irrigation water was significantly related to the daily fraction of PAR intercepted ($y = 99.26 + 6.31 \times f_D$; $R^2 = 0.62$; $P = 0.001$). The water applied (irrigation plus effective annual rainfall) under deficit irrigation to maintain the threshold of SWP -2.0 MPa over 3 years of study resulted in water savings of 72, 65 and 54 % in comparison with controls at 476, 317 and 238 trees ha⁻¹, respectively.

We scheduled irrigation using Eq. 1, with a reduction factor equal to fraction of daily PAR intercepted. Figure 2 shows the relationship between fraction of daily PAR intercepted and percentage of ground cover measured on the same days, with the fitted regression:

$$f_D = 1.33 \times \%GC \text{ for}$$

$$10 \% \leq \%GC \leq 45 \% \left(P = 0.002; R^2 = 0.43 \right) \quad (5)$$

Figure 2 also includes the functions between K_r and %GC for isolated trees previously suggested by Fereres

et al. (1981) for almond and by Fereres et al. (2012) for several tree species. Comparing K_r estimated through f_D and the equation proposed by Fereres et al. (1981), over the 3-year period water savings of 22, 18 and 8 % were obtained in the densities of 476, 317 and 238 trees ha⁻¹, respectively.

Vegetative growth

Crown volume and trunk perimeter did not respond the interaction between planting density and irrigation regime; hence, we analyse the effects of each factor individually. Water deficit affected crown volume and trunk perimeter on both per plant and per hectare basis (Fig. 3; Table 3). Significant differences between control and deficit irrigation started in the autumn of 2010 for trunk perimeter and in the autumn of 2011 for crown volume (Fig. 3). Over the experimental period, the trunk perimeter increased by 39 % in controls and 29 % under deficit irrigation, while canopy volume increased 6190 m³ ha⁻¹ in controls and 4093 m³ ha⁻¹ under deficit irrigation for the same period (Table 3). Tree density did not affect crown volume or trunk perimeter of individual trees (Fig. 3). The increase in crown volume and trunk perimeter per ha, and daily PAR

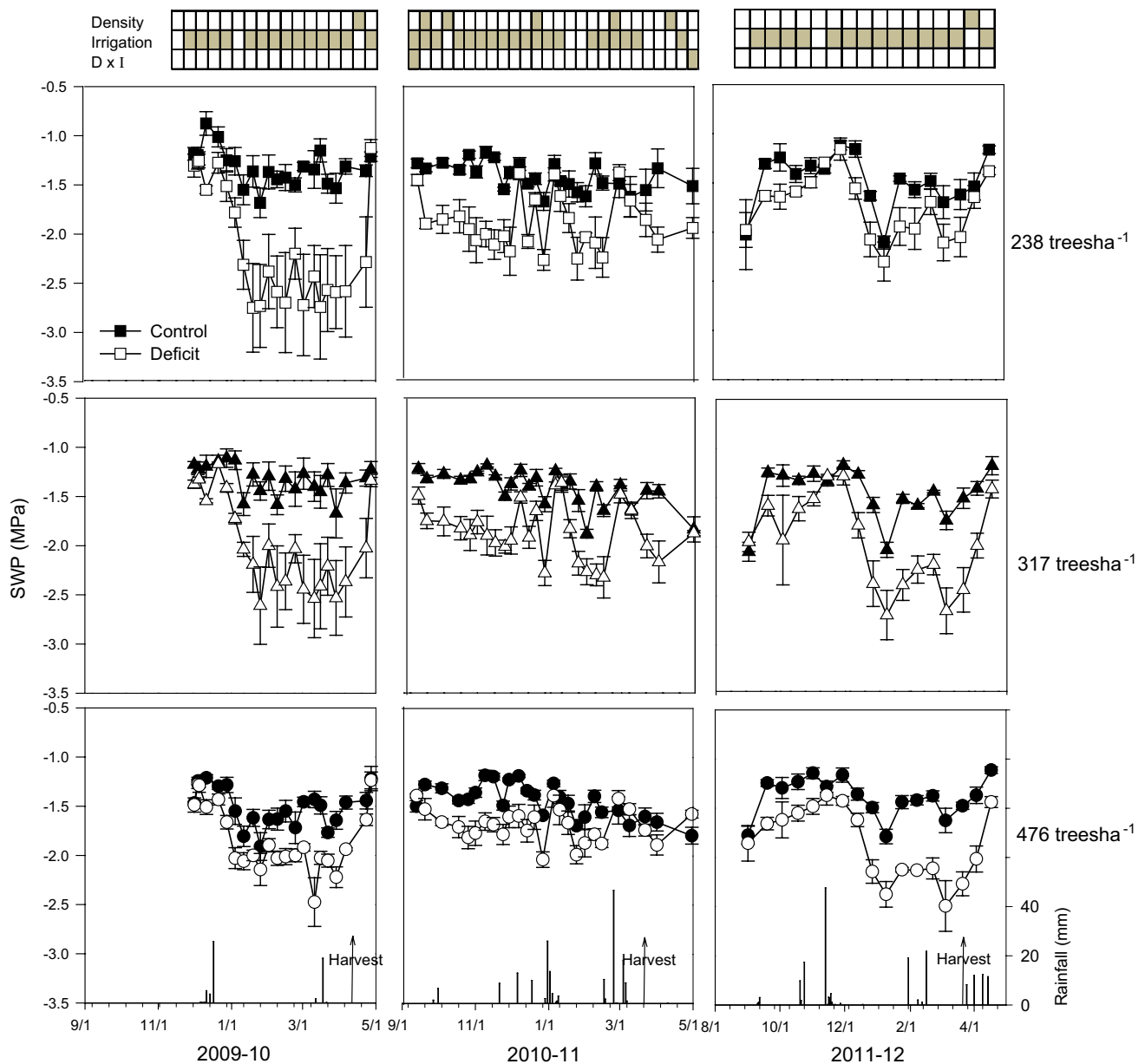


Fig. 1 Dynamics of midday stem water potential (SWP) of olive trees in response to two irrigation levels (control, closed symbols and deficit irrigation, open symbols) and three tree densities during the three growing seasons in Mendoza. Grey squares in top panel indi-

cate significant effects of tree density, irrigation and interaction density \times irrigation at $P < 0.05$. Error bars are two standard errors of the mean. Vertical bars indicate the rainfall

interception were significantly higher with augmented tree density. The density of 476 trees ha^{-1} achieved 28 and 49 % more canopy volume per hectare than 317 and 238 trees ha^{-1} , respectively (Table 3).

At the end of the experimental period, adjacent plants at the highest density (3 m between trees) overlapped (horizontal width in the row direction 3.01 ± 0.05 m), while in lowest density, adjacent trees (6 m between trees) were clearly separated (horizontal width in the row direction 3.43 ± 0.10 m).

Oil yield and its components

The interaction between tree density and water regime was not statistically significant for yield and its components (Table 4); therefore, we discuss yield responses to density and irrigation separately. Fruit yield per tree at the highest density was 30 % higher than intermediate density and 44 % higher than at the lowest density (Table 4), although these differences were not statistically significant ($P = 0.107$), due to the large intra- and inter-annual

variability among trees under same density as indicated by the standard errors in Table 4. Owing to the trend for higher yields per tree at higher densities, the increase in yield was more than proportional and highly significant with the increased number of trees per hectare: fruit yield per ha at 476 trees ha⁻¹ was 50 % higher than at 317 trees ha⁻¹ and 70 % higher than at 238 trees ha⁻¹. Water deficit decreased fruit yield by 25 % with respect to control in both terms, per tree and per hectare, although no significant differences were detected with ANOVA. However, fruit yield per plant decreased at a consistent rate of 0.07 kg tree⁻¹ per MPa days of *Sψ* (Fig. 5a). Alternate bearing was less evident in the highest density and fully irrigated controls in comparison with the lowest tree density and water deficit, respectively. The effect of treatments on oil yield resembled those found for fruit yield (Table 4).

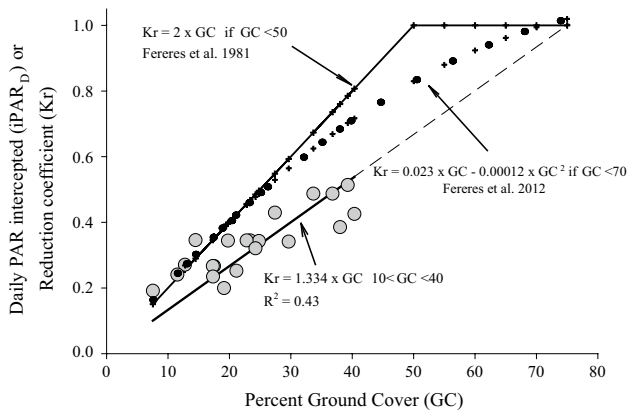
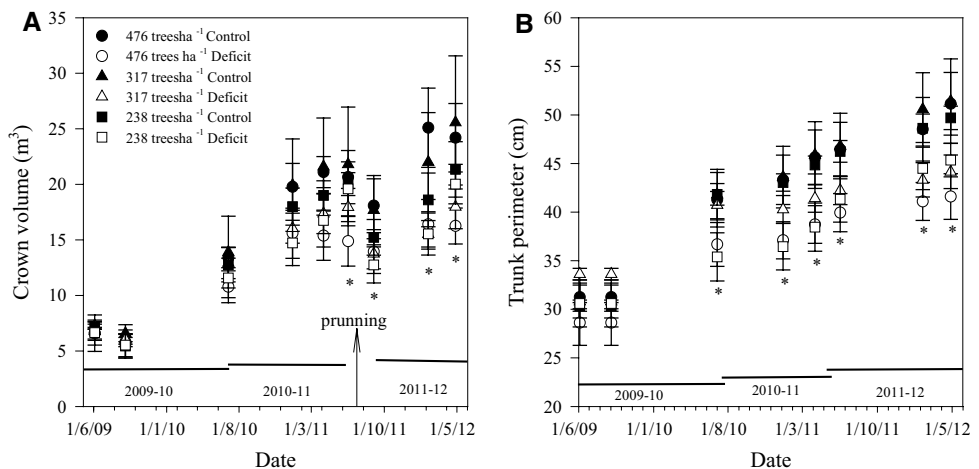


Fig. 2 Reduction coefficient (K_r) estimated from daily fraction of PAR intercepted (dash line) over a range of per cent ground cover (dash line) and compared with K_r estimated by Fereres et al. (1981) (solid line) and Fereres et al. (2012) (dotted line)

Fig. 3 Evolution of crown volume (a) and trunk perimeter (b) of olive trees during 3 years in experiments combining three planting densities and two irrigation regimes (control, closed symbols and deficit irrigation, open symbols). The asterisks indicate significant effects irrigation at $P < 0.05$. No significant effect was detected for tree density or tree density \times irrigation interaction. Vertical bars represent two standard errors of the mean



Tree density and irrigation did not affect dry fruit weight and pulp/pit ratio (Table 4). Fruit number increased continuously between seasons, explaining the seasonal effect on oil yield (Table 4). Fruit oil concentration on a dry pulp basis was not significantly different among tree densities. Across densities and seasons, water deficit significantly reduced oil concentration by around 3 % with respect to controls ($P < 0.001$).

Fruit water concentration was affected by both tree density and irrigation (Table 4). The highest tree density showed higher water concentration than the other two densities. Fruit water concentration was about 4 % lower under water deficit than in controls. Fruit water concentration decreased with increasing *Sψ* (Fig. 4a, $R^2 = 0.40$; $P < 0.01$). Earlier maturity was observed with water stress, and it was not affected by tree density ($P = 0.075$). The seasonal variation in the maturity index (Table 4) was related to the seasonal difference in fruit load (Fig. 4b, $R^2 = 0.65$; $P < 0.001$).

Irrigation water use efficiency

Tree density, irrigation and their interaction all significantly affected the IWUE (Table 2). Across seasons and irrigation levels, 476 trees ha⁻¹ had IWUE that were 14 and 65 % higher than those of 317 and 238 trees ha⁻¹, respectively. Comparing irrigation levels across tree densities and seasons, IWUE under water deficit was 2.0-fold higher than in controls. The interaction between tree density and irrigation level ($P < 0.05$) had a significant effect on both IWUE_f and IWUE_o (Table 2). The combinations 476 and 317 trees ha⁻¹ under deficit irrigation had higher efficiencies than the other combinations. The IWUE_o was correlated with the seasonal *Sψ* according to a quadratic relationship (Fig. 5); maximum IWUE_o corresponded with *Sψ* = 180 MPa days.

Table 3 Total increment of crown volume and trunk perimeter from December 2009 to April 2012 (per tree and per hectare) as affected by tree density (trees ha⁻¹) and irrigation (control, CT vs. deficit irrigation, DI)

Source of variation	Increment crown volume		Increment trunk perimeter		PAR intercepted	
	(m ³ tree ⁻¹)	(m ³ ha ⁻¹)	(m tree ⁻¹)	(m ha ⁻¹)	Initial (%)	Final (%)
Density						
476	14.5	6909	0.16	78	34.2	44.5
317	15.4	4898	0.15	49	23.7	32.1
238	15.2	3618	0.17	41	19.1	24.4
Irrigation						
CT	17.8	6190	0.20	69	25.9	36.9
DI	12.3	4093	0.13	43	25.4	30.4
LSD (0.05)						
LSD _{Density}	ns	2198.3	ns	16.6	4.02	5.43
LSD _{Irrigation}	4.93	1794.9	0.032	13.6	ns	4.43
LSD _{D×I}	ns	ns	ns	ns	ns	ns

The percentage daily of PAR intercepted at the beginning and end of the experiment is also included
The least significant difference (LSD) is presented when ANOVA indicated significant effect ($P < 0.05$)
ns no significant ($P < 0.05$)

Table 4 Fruit and oil yield and their components (\pm SE) as affected by tree density (trees ha⁻¹), irrigation level and season in terms of tree and hectare in olive (cv Frantoio) orchards in Mendoza, Argentina

Source of variation	Tree level								Hectare level		
	Fruit yield (kg tree ⁻¹)	Fruit number per tree	Fruit dry wt (g)	Oil yield (kg tree ⁻¹)	OCDB (%)	Pulp/pit ratio	FWC (%)	Maturity index	Fruit yield (t ha ⁻¹)	Oil yield (t ha ⁻¹)	ABI (%)
Density											
476	12.2 \pm 1.89	3663 \pm 83.0	1.4 \pm 0.04	1.9 \pm 0.30	50.3 \pm 1.31	5.2 \pm 0.07	50.1 \pm 0.69	3.2 \pm 0.16	5.8 \pm 0.90	1.0 \pm 0.10	40 \pm 8.1
317	8.6 \pm 1.68	2720 \pm 73.1	1.4 \pm 0.03	1.5 \pm 0.27	51.6 \pm 0.71	5.0 \pm 0.08	47.5 \pm 0.74	3.6 \pm 0.14	2.7 \pm 0.53	0.5 \pm 0.09	49 \pm 6.8
238	6.8 \pm 1.94	2250 \pm 80.2	1.4 \pm 0.05	1.2 \pm 0.34	50.6 \pm 0.97	5.2 \pm 0.09	48.6 \pm 0.93	3.5 \pm 0.16	1.6 \pm 0.46	0.3 \pm 0.08	65 \pm 7.3
Irrigation											
CT	10.6 \pm 1.67	3289 \pm 70.1	1.3 \pm 0.02	1.8 \pm 0.28	52.4 \pm 0.63	5.2 \pm 0.06	50.6 \pm 0.49	3.3 \pm 0.10	3.8 \pm 0.57	0.7 \pm 0.10	49 \pm 6.2
DI	7.7 \pm 1.35	2467 \pm 59.6	1.4 \pm 0.04	1.3 \pm 0.22	49.3 \pm 0.89	5.1 \pm 0.06	46.8 \pm 0.64	3.6 \pm 0.14	2.9 \pm 0.64	0.5 \pm 0.09	54 \pm 7.2
Season											
2009–2010	6.3 \pm 1.11	2100 \pm 44.7	1.3 \pm 0.03	1.0 \pm 0.20	48.1 \pm 1.30	5.3 \pm 0.04	48.4 \pm 0.83	4.0 \pm 0.10	2.5 \pm 0.5	0.4 \pm 0.09	–
2010–2011	10.1 \pm 2.32	3884 \pm 97.4	1.5 \pm 0.05	1.7 \pm 0.37	50.5 \pm 0.56	4.7 \pm 0.05	47.7 \pm 0.92	3.4 \pm 0.16	3.6 \pm 0.8	0.6 \pm 0.11	–
2011–2012	11.1 \pm 1.92	4549 \pm 84.7	1.3 \pm 0.03	2.0 \pm 0.32	53.9 \pm 0.81	5.3 \pm 0.07	49.9 \pm 0.58	3.0 \pm 0.12	4.1 \pm 0.8	0.7 \pm 0.12	–
LSD (0.05)											
LSD _{Density}	ns	ns	ns	ns	ns	ns	1.85	ns	1.86	0.30	23.9
LSD _{Irrigation}	ns	ns	ns	ns	2.22	ns	1.51	0.30	ns	ns	ns
LSD _{Season}	ns	2127.4	0.11	0.85	2.72	0.17	ns	0.36	ns	ns	ns
LSD _{D×I}	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

The least significant difference (LSD) is presented when ANOVA indicated significant effect ($P < 0.05$)

ns no significant ($P < 0.05$)

CT control, DI deficit irrigation, OCDB oil concentration dry weight basis, FWC fruit water concentration, ABI alternate bearing index

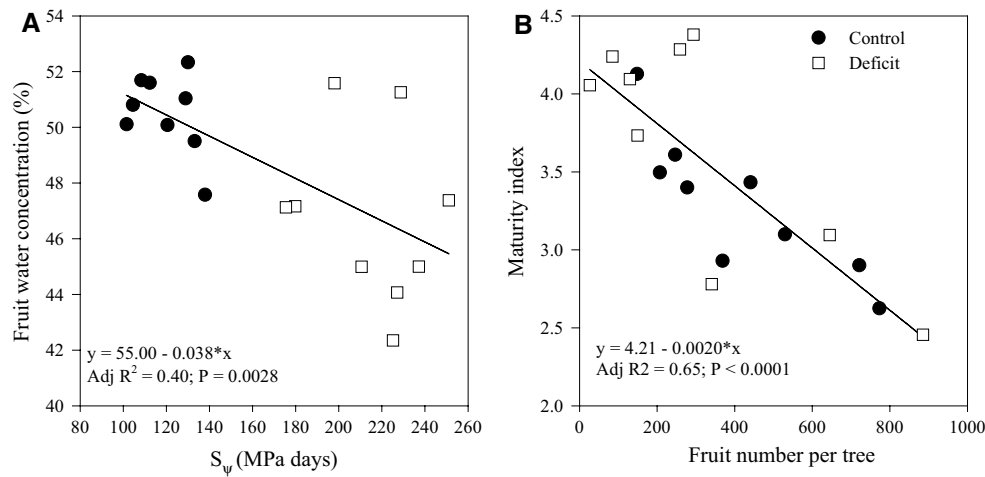
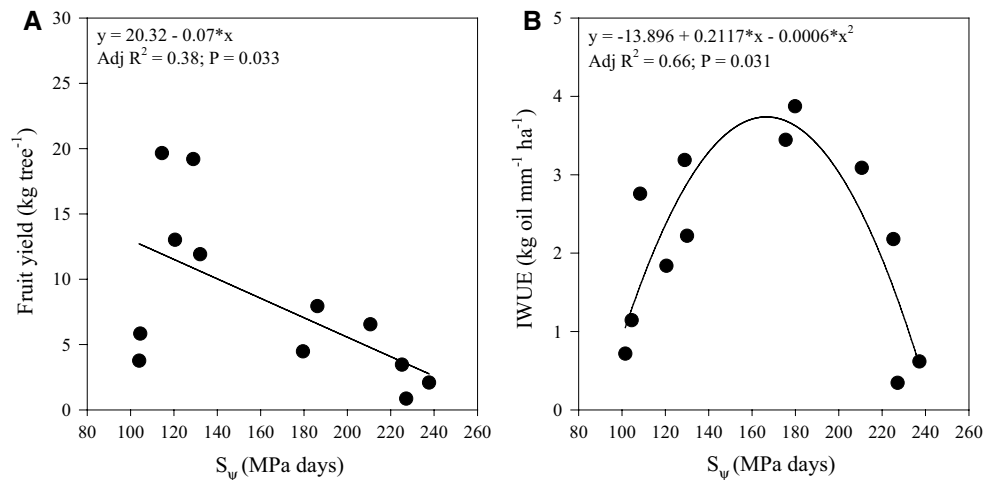


Fig. 4 Relationship between **a** fruit water concentration and seasonal water stress integral (S_{ψ}) and **b** maturity index (unit less) and fruit number per tree, in two irrigation levels (control, closed symbols and

deficit irrigation, open symbols) and three tree densities (476, 317 and 238 trees ha^{-1}) during the three growing seasons in Mendoza

Fig. 5 Relationship between seasonal water stress integral (S_{ψ}) from September to April and **a** fruit yield and **b** irrigation water use efficiency for oil yield ($IWUE_o$) in olive orchards in Mendoza, Argentina. Three tree densities were combined with water deficit and fully irrigated controls. The data of the first season (2009–2010) are not included because the treatments were initiated after fruit set



Discussion

Scheduling irrigation with the water balance method involves uncertainty in relation to different climates, soil characteristics and plant material (Reynolds and Naylor 1994), whereas plant-based methods are better suited to account for these factors (Girona et al. 2006; Fernández and Cuevas 2010). The midday SWP is widely considered a reliable plant-based water status indicator in olive (e.g. Goldhamer et al. 1999; Moriana et al. 2003). In terms of the treatment where 100 % of the crop's water needs were provided, we obtained a SWP threshold value of -1.3 MPa during spring (before pit hardening) and a SWP of -1.5 MPa for summer–autumn (following pit hardening to harvest). Although we had little antecedents for our conditions, these values were similar to thresholds recently obtained by Moriana et al. (2012) for irrigation scheduling

under non-water stress conditions of olive in southern Spain.

In 2009–2010 and 2011–2012, the SWP threshold established for deficit irrigation before starting the experiment (-2.5 MPa) was partially achieved. Deficit irrigated trees reached SWP ~ -1.8 MPa during spring, and ~ -2.25 MPa from summer to harvest, with no significant reduction in oil yield. In 2010–2011 above-average rainfall precluded the achievement of the target water deficit. A single SWP threshold for the whole season, however, does not account for seasonal dynamics of plant water status related to both changes in evaporative demand (Olivo et al. 2009) and the shift from higher to lower source: sink ratio after fruit set (Sadras and Trentacoste 2011; Trentacoste et al. 2011; Naor et al. 2013). Hence, using stage-specific SWP thresholds would help refining water management. The proposition of two thresholds—one before and one after pit

hardening—seems a sensible compromise to capture these major sources of variation in plant water status while maintaining a relatively simple protocol (Moriana et al. 2012). Season-dependent thresholds have been recommended for other horticultural crops (Marsal and Girona 1997; Girona et al. 2009; Acevedo-Opazo et al. 2010).

K_r is an empirical coefficient relating the K_c of a young orchard (or incomplete cover) with respect to K_c of a mature orchard (Feres et al. 2012). Differences in K_r between young and mature orchards have been associated with the per cent ground cover or midday intercepted radiation (peach, Ayars et al. 2003; grapevine, Williams and Ayars 2005; apple and pear, Girona et al. 2011). We used daily fraction of the interception of radiation as K_r due (1) to the absence of preliminary lysimeter studies in olive on the relationship between K_c and interception of radiation and (2) to the reduction in the bias associated with K_r estimated as a function of ground cover which does not account for gaps within the tree shade, effect of adjacent trees and vertical growth of the canopy. Irrigation scheduling in the control treatment with the daily fraction of PAR intercepted as K_r allowed accurate interpretation of crop water needs under a range of tree densities and three growing seasons, with insignificant differences in midday SWP among tree densities. Over the 3-year period, irrigation scheduling had a water saving average of 16 % (across densities), compared to the use of K_r initially proposed by Feres et al. (1981).

In addition to the effects on current season yield, however, thresholds for deficit irrigation need to account for long-term effects on vegetative growth, which in turn can affect long-term yield. A seasonal average of SWP ~ -2.0 MPa for deficit irrigation reduced vegetative growth in our experiment. Trunk growth was more sensitive than crown volume, as found in previous works (Moriana et al. 2003; Tognetti et al. 2006; Fernandes-Silva et al. 2010). On the other hand, vegetative growth was more sensitive to drought than the reproductive process, as has been widely observed in olive and other crops (Hsiao 1973; Pérez-López et al. 2007; Moriana et al. 2012). This differential sensitivity may provide an advantage for controlling the size of plants with slight yield reduction according to the SWP threshold. This is of particular interest in mature high and super-high-density orchard (Tognetti et al. 2006). However, scarce efforts have been made to obtain SWP threshold for vegetative control. This can be explained because winter rainfalls in Mediterranean climates, where most of the research in olives has been done, make redundant the management of plant water status early in the growing season when vegetative growth occurs (Fig. 3). By contrast, there are opportunities for the active management of early season water and vegetative under the climate conditions of western Argentina.

High-density plantations required larger amounts of water per ha than their lower density counterparts. However, in the seventh and eighth years after planting, water depth applied at the tree level was higher at lower density. In these growing seasons, for the 476 trees ha⁻¹ treatment, crown diameter reached near 3 m, whereas crown diameter was below the 6 m assigned to the planting area at 238 trees ha⁻¹. The low ground cover at low planting density could result in less capture of water from the emitters farther from the trunk, in addition to greater loss through soil evaporation. Furthermore, the greater separation between adjacent canopies potentially caused a “clothesline effect”, a condition in which hot and dry air passes between trees, increasing transpiration (Ritchie and Johnson 1990).

We observed a large variability of yield per tree, which could be attributed to characteristics of cultivar used in our conditions, i.e. cv Frantoio shows a long unproductive period (León et al. 2007) and high alternate bearing pattern and intra-annual yield variability accentuated in the early productive years. Consequently, more experimental years and replicates are needed for firm conclusions about density effect on yield at tree level. Across tree densities, water deficit induced a slight fruit and oil yield reduction in 25 %, compared to the control. It was achieved with a 65 % reduction in the total amount of water applied, which resulted in an increase in IWUE_o from 1.4 to 4.6 kg ha⁻¹ mm⁻¹. Owing to the effects of management practices, irrigation system and soil evaporation rates, comparison of IWUE with previous studies is difficult (Iniesta et al. 2009). However, the trend of increasing the yield per unit irrigation applied under deficit irrigation in our study has been widely reported in olive (Goldhamer et al. 1999; Wahbi et al. 2005; Iniesta et al. 2009) and other tree crops (Feres et al. 2012). The increase in the number of plants per hectare also significantly increased the IWUE in both fruit and oil yield terms, registering IWUE up to 50 % higher at 476 trees ha⁻¹, with regard to 238 trees ha⁻¹. The interaction of tree density \times irrigation strategies was significant for IWUE. This significant interaction can be explained because the reduction in the oil yield was directly proportional to reduction in applied water at the lowest tree density. By contrast, at intermediate and higher tree densities, the oil yield reduction was proportionally less than the reduction in irrigation water, hence increasing IWUE.

Fruit water concentration at harvest is important because high water concentration in fruit could produce emulsions with reduced oil extractability (Motilva et al. 2000; Gratani et al. 2006). Previously, we observed that fruit oil and water concentrations were inversely related; oil deposition replaces water within the fruit causing a progressive water reduction (Trentacoste et al. 2012). In this study, fruit water concentration decreased linearly as $S\psi$ increased at a rate of 0.04 % MPa days; this was also associated with reduction in fruit oil concentration on dry weight basis (Table 4). To develop SWP thresholds for target fruit water

concentration, future research is needed in order to obtain the relationship between both water and oil fruit concentrations with industrial oil yield, to know whether the reduction in fruit oil concentration by water stress is compensated with increased industrial oil yield, with the advantage of saving irrigation water.

IWUE was also related to the seasonal $S\psi$, where a value of 180 MPa days maximized IWUE. This relationship has not been previously reported and is of great interest in areas where water is the most limiting factor, as is the case of the Mendoza Province. Furthermore, maximizing water use efficiency may be economically more profitable than maximizing yields in some production systems (Wallace 2000; Geerts and Raes 2009).

Concluding remarks

Our work has shown that midday SWP is affected by irrigation strategies but not by ground cover. Under our experimental conditions, in olive trees irrigated with 100 % of ET_c were obtained midday SWP thresholds of -1.3 and -1.5 MPa before and after pit hardening, irrespective of tree density and seasonal conditions. A reduction coefficient based on daily radiation intercepted helped to correctly interpret the crop water needs over a wide ground cover range. In the eighth year after planting, the distance between trees (from 3 to 6 m) unaffected both vegetative and reproductive growth, while water deficit affected vegetative growth with slight effect on oil yield. The interaction tree density \times irrigation was only significant for irrigation water efficiency, i.e. water regime did not affect the efficiency at low tree density, while efficiency increased under water deficit at intermediate and high tree density. IWUE was nonlinearly related to seasonal water stress integral, where maximum efficiency corresponded to $S\psi$ 180 MPa days. Owing to the multiple effects of water deficit on traits of agronomic and economic interest, including oil yield, concentration of water in fruit, oil extractability, water use efficiency and long-term vegetative growth, an optimum SWP threshold is unlikely (Niklas 1994; Farnsworth and Niklas 1995).

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