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Summer deficit irrigation in a hedgerow olive orchard cv. Arbequina: relationship between soil and tree water status, and growth and yield components

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Abstract

Stem water potential (Ψ_{stem}) is a useful tool for irrigation scheduling in tree crops, provided threshold values for growth and production are determined for each physiological period. Four irrigation treatments were evaluated in a hedgerow olive orchard. Control (CON) was irrigated using soil water sensors to maintain the root zone close to field capacity. Severe water deficits were applied by irrigating at 30% CON from end of fruit drop to end of July (DI-J) or from end of July until beginning of oil synthesis (DI-A). Less severe water deficit was applied in July and August by irrigating at 50% CON (DI-JA). Continuous measures of soil moisture, Ψ_{stem} and shoot length were recorded in all treatments. Fruit dry weight and oil content were measured at the end of the experimental period and at harvest. Relative extractable soil water to 0.8 m depth (REW) and Ψ_{stem} were highly correlated and influenced by irrigation treatment. Shoot growth, fruit characteristics and oil production were correlated to Ψ_{stem}. Shoot growth was reduced by 50% relative to CON by irrigating at Ψ_{stem} of –1.3 MPa. Fruit dry matter and oil content (g fruit^{-1}) were linearly reduced as mean summer Ψ_{stem} decreased. Oil production was highly related with Ψ_{stem} in August but not in July. Water can be saved in July by irrigating at Ψ_{stem} of –2.9 MPa but Ψ_{stem} should be maintained higher than –2.0 MPa in August to prevent decrease of oil production.

Additional key words: oil production; *Olea europaea* L.; stem water potential; threshold values for irrigation management; vegetative and fruit growth.

Introduction

Although olive (*Olea europaea* L.) is among the most drought resistant plant species, large production increases are commonly obtained when irrigation is applied in dry climates (Moriana *et al.,* 2003). In the case of superintensive hedgerow olive orchards, irrigation is needed to hasten canopy development and early production. After that, high oil yields are required to counteract the high capital cost of orchard establishment. In many olive cultivation areas, irrigation water is scarce and expensive and so deficit irrigation strategies are required that can optimize its use. One such strategy is regulated deficit irrigation (RDI) that reduces irrigation during known drought-resistant phenological stages (Chalmers *et al.,* 1986). The approach has been utilized successfully in various fruit trees as described in reviews by Ruiz-Sánchez *et al.* (2010) and Behboudian *et al.* (2011). In olive, previous studies have shown that controlled water deficit does not reduce olive yield when applied during certain summer periods (Goldhamer, 1999; Alegre *et al.,* 2002; Lavee *et al.,* 2007). Water deficit can be applied from around the end of fruit drop until the start of oil synthesis. When applied earlier, deficit irrigation can also reduce vegetative growth, but at the expense of greater flower

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Abbreviations used: CON (control); DI-A (deficit irrigation from the end July until the beginning of oil synthesis at the end of August); DI-J (deficit irrigation from the end of fruit drop to the end July); DI-JA (deficit irrigation in July and August); ETo (reference evapotranspiration); GDD (growing degree days); RDI (regulated deficit irrigation); REW (relative extractable water);Ψ (water potential); Ψ_{leaf} (leaf water potential); Ψ_{pd} (pre-dawn water potential); Ψ_{stem} (stem water potential); θ (soil water content).

and fruit drop, because both processes occur together. When applied during oil synthesis, oil production will be reduced (Tognetti *et al.,* 2006).

Successful application of RDI requires maintenance of plant water status above a stress threshold (Jones, 2004). This can be achieved with indicators of soil or plant water status. It is, however, difficult to establish fixed threshold soil moisture values for irrigation scheduling as many factors are involved-soil characteristics (mainly texture, structure and depth), sensor location relative to emitters in localized irrigation, measurement method and calibration, root development, plant hydraulic resistance and evaporative demand (Sadras & Milroy, 1996). Consequently, universal values cannot be obtained and threshold values of soil water content should be established for each specific location. By contrast, tree water status that responds to the interaction of soil moisture availability, atmospheric evaporative demand and canopy conductance may best provide thresholds for irrigation scheduling (Naor, 2006).

Plant physiological processes are dependent on cell turgor potential (Hsiao *et al.,* 1976) but since this parameter is not easily measured, plant water potential (Ψ), readily measured with a pressure chamber (Scholander *et al.,* 1965), is widely used in research, and increasingly in commercial practice for measuring plant water status. Water potential varies diurnally, especially in leaves (Ψ_{leaf}) which are at the end of the internal flow path of transpiration, and is usually highest at pre-dawn (Ψ_{pd}) when it is most highly correlated with soil water content in the root zone. Water potential of covered (non-transpiring) leaves is less variable diurnally and is taken to be closer to that in the xylem of the stem (Ψ_{stem}) (Begg & Turner, 1970). Studies in orchard trees have established that differences in Ψ_{stem} between irrigation treatments were greater than differences in Ψ_{leaf}, and these differences were better correlated to soil water availability (Garnier & Berger, 1985; McCutchan & Shackle, 1992; Naor *et al.,* 1995), stomatal conductance (McCutchan & Shackel, 1992; Naor *et al.,* 1995), shoot growth (Shackel *et al.,* 1997), fruit size (Naor *et al.,* 1995; Shackel *et al.,* 1997) and yield (Naor *et al.,* 1995; Naor, 2006).

In a previous paper, the crop and oil-yield data as well as reproductive components of this experiment were reported (Gómez-del-Campo, 2013). The objectives of the present study are to analyze interactions of soil- and tree-water status with components of fruit yield and shoot growth of trees in a superintensive hedgerow olive orchards (4 × 2 m) subjected to RDI strategies during summer and to establish threshold values of Ψ_{stem}.

Material and methods

Experimental orchard

The experiment was conducted in a 45 ha commercial orchard planted in 1997 with cv. Arbequina in Puebla de Montalbán, Toledo, Spain (39° 48' N; 04° 27' W; 516 m asl). The area is characterized by low rainfall (average annual of 395 mm), high evaporative demand (average annual ETo of 1,180 mm), and a long frost-prone period (November to March). Soil is clay loam (Haploxeralf typic) with an effective rooting depth of 0.60 m comprised of three layers of 0.20 m each. The texture of the three horizons in sequence was clay loam, clay loam and sandy-clay loam with stones occupying 9, 9 and 12% of horizon volumes, respectively. Tree spacing was 4 × 2 m (1,250 trees ha^{-1}) with rows oriented 20° N of EW. At the beginning of the experiment, hedgerows were 2.3 m high and 1.1 m wide. Weeds were controlled using a non-residual herbicide, and fertilizer was applied according to leaf analyses carried out in July each year. Tree shape (3 m high and 1 m width) was controlled by pruning.

Irrigation treatments

Four irrigation treatments were maintained during the 2007, 2008 and 2009 seasons: control (CON), deficit irrigation from the end of fruit drop to the end July (DI-J), deficit irrigation from the end July until the beginning of oil synthesis at the end of August (DI-A) and deficit irrigation in July and August (DI-JA). Deficit irrigation treatments were irrigated as the control except during the specified periods when 30% of CON irrigation levels were applied to DI-J and DI-A and 50% to DI-JA. Amounts of irrigation water applied differed from year to year according to climatic conditions. Each treatment was replicated four times in a complete randomized block design where each replicate comprised 36 trees (12 trees in three adjacent rows). The 10 central trees in the centre row of each replication were used for measurement. Three of these trees were selected for harvest. The irrigation system consisted of a single line with drip emitters of 3 L h^{-1} spaced 0.50 m apart. Further details of irrigation treatments and climatic conditions were reported by Gomez-del-Campo (2013).

Irrigation scheduling

CON trees were irrigated according to continuous readings of six Watermark™ sensors and one soil temperature sensor connected to a data logger (Irrometer, CA, USA). The standard manufacturer calibration was used to convert soil electrical conductivity measured by the sensors into soil matric water potential. Sensors were placed in pairs at 0.3 m depth and 0.3 m from emitters adjacent to the trunks of three representative trees. Irrigations of 6 h duration were applied from spring until 15 August when sensors indicated a mean soil water potential of –0.03 MPa. Thereafter, threshold potential for irrigation was lowered to –0.06 MPa until the end of the irrigation season in order to harden the trees for autumn frost. Detailed measurements at two sites revealed that irrigation of 6 h duration wetted the soil to 0.6 m depth, and therefore to the potential effective rooting depth without excessive drainage measured with a capacitance probe at 0.70 m.

Soil and plant water status

Soil water content (θ, $m^3\,m^{-3}$) was measured hourly from 21 March to harvest with four sensors, three at root depth (0.10, 0.20 and 0.40 m) and one at drainage depth (0.70 m) using a capacitance probe (Enviroscan, Sentek Pty. Ltd, Australia). Two access tubes of 1.0 m length were installed in each treatment in the wetted volume at a distance of 0.30 m from a dripper and an olive trunk. At each measurement, mean soil water content to 0.8 cm depth was calculated considering the spacing between sensors. Relative extractable water (REW) was calculated by the equation $REW = (\theta - \theta_{min})/(\theta_{max} - \theta_{min})$, where θ is the actual soil water content, θ_{min} and θ_{max} were the minimum and maximum soil water content measured during the experiment in each tube, respectively.

Stem water potential (Ψ_{stem}, MPa) was measured at solar noon on days prior to irrigation using a pressure chamber (Soil Moisture Equip., Santa Barbara, CA, USA). Four shoot tips per treatment were selected on the shaded side of the row near the trunk. Shoot tips were covered with aluminum foil for 1 h prior to measurement to allow leaf water potential to equilibrate with stem water potential (Begg & Turner, 1970).

Vegetative growth

Shoot length was measured on two lateral shoots in each of three trees per replicate. Tagged stems were de-fruited. Measurements were carried out periodically from May to October. Shoot length and Ψ_{stem} were measured on the same day. Shoot growth rate was calculated relative to the accumulation of growing degree days (GDD) using 7°C as a baseline (Orlandi *et al.,* 2010).

Fruit characteristics

A sample of 100 fruits was collected at the end of treatment period on 02/09/07, 31/08/08 and 24/08/09 from the middle part of the hedgerow on the south side. Three subsamples of 25 g were weighed after oven-drying at 105°C until constant weight. Oil content was measured by nuclear magnetic resonance (MiniSpec, MQ-10, Bruker, Madison, USA) using the method described by Del Río & Romero (1999).

Final harvests were made on 12/11/2007, 05/11/2008 and 30/10/2009 when fruit was removed from the three selected trees per treatment and repetition. Yield of each tree was weighed fresh on collection from which a sample of 450 g was extracted. Samples were divided into subsamples of 25 g that were each reweighed and again after drying, fruit were counted. Oil content was determined on dry basis as described previously.

Statistical analysis

Data were subjected to analysis of variance using MSTAT-C (University of Michigan, USA). Significant differences ($p < 0.05$) were used to separate means of parameters evaluated between irrigation treatments using Duncan's multiple range test. Regression equations between Ψ_{stem} and REW, shoot growth and oil production were established with Excel 10 (MS, Redmond, WA, USA).

Results

Amounts of irrigation water applied differed from year to year according to the climatic conditions. CON received 221, 284 and 402 mm in the 2007, 2008 and 2009 seasons, respectively, while DI-J, DI-A and DI-JA received 16, 22 and 27% less water than CON, respectively.

Soil and plant water status

The irrigation treatments modified REW during summer, in response to the different amounts of water applied (Fig. 1). REW values in July were significantly higher in CON and DI-A (Table 1) than in DI-J and DI-JA, while in August REW values were higher in CON and DI-J. Mean summer REW was significantly lower in DI-JA than in the other treatments. Although all irrigation treatments received the same amount of water in autumn, summer irrigation treatments produced significant differences in 2008 and 2009 when DI-JA had the lowest REW values in autumn. Seasonal REW in CON was higher in 2008 and 2009 than in 2007, mainly due to higher values in autumn in those two years.

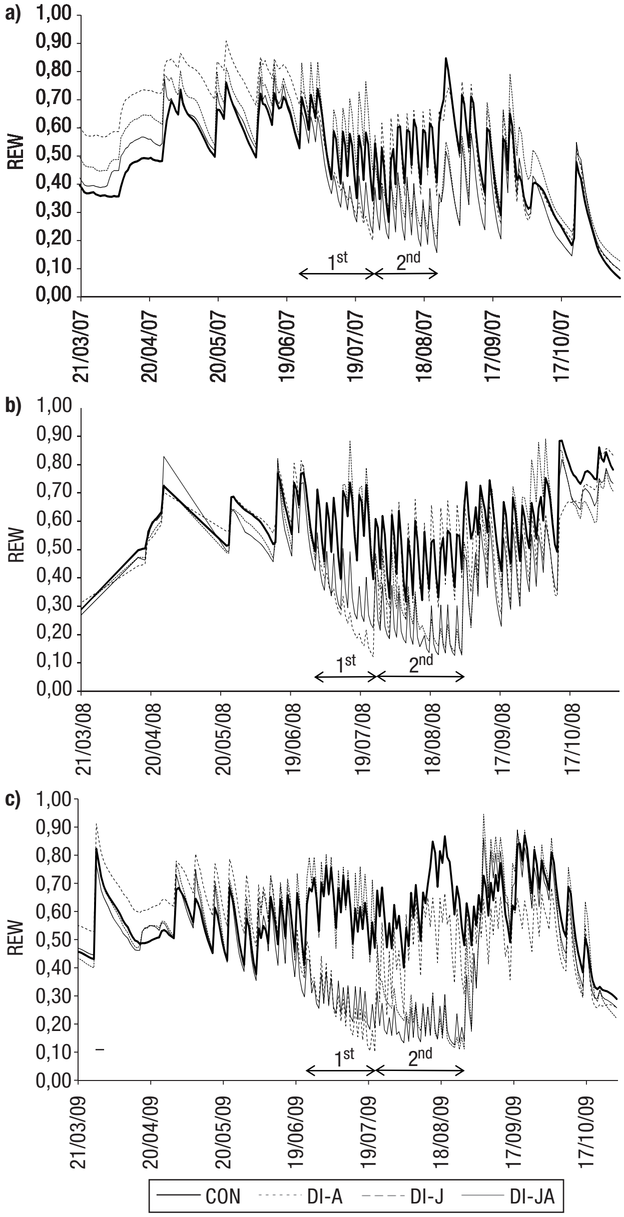

Figure 1. Relative extractable water (REW) to 0.8 m depth at 0.30 m from a drip emitter in a control (CON) and three deficit-irrigation treatments (DI-J, DI-A and DI-JA) in 2007 (a), 2008 (b) and 2009 (c). Arrows indicate first and second summer irrigation periods.

The highest value of Ψ_{stem} (–0.2 MPa) was recorded in 2007 before the start of irrigation treatments (Fig. 2), and the lowest value (–4.7 MPa) in DI-JA on 25/08/09. Ψ_{stem} was significantly different once the irrigation treatments were applied. The effect of irrigation was also observed in Ψ_{stem} on some autumn days in 2007 and 2008 (Fig. 2).

Relationships between Ψ_{stem} and REW (0.8 m average) were analyzed on pooled data of all three seasons (164 data pairs) (Fig. 3). Ψ_{stem} (–MPa) was more highly correlated to REW ($R^2 = 0.77$) than with actual values of soil moisture content ($R^2 = 0.68$). When each treatment was analyzed separately better fits were obtained: DI-A ($y = -1.99\ln(x) + 0.37$, $R^2 = 0.85$); DI-J ($y = -1.73\ln(x) + 0.54$, $R^2 = 0.85$); DI-JA ($y = -2.02\ln(x) + 0.02$, $R^2 = 0.84$), where $y = -\Psi_{stem}$ and $x = \text{REW}$. The relationship for CON was less precise ($y = -1.21\ln(x) + 1.00$, $R^2 = 0.47$), due to the smaller range in REW. The relationships between Ψ_{stem} and REW for each treatment were used to calculate Ψ_{stem} for each day. Mean values for each period and mean values on the days prior to each irrigation are presented in Table 2 and Table 3, respectively. Mean seasonal Ψ_{stem} revealed that CON was more stressed in 2007 (–2.0 MPa) than in 2008 and 2009 (–1.7 MPa). The highest mean Ψ_{stem} was recorded in 2007 spring in DI-J and DI-JA (–1.1 MPa) and the lowest in August 2009 DI-J and DI-JA (–3.4 MPa). Spring and autumn Ψ_{stem} were not significantly different between treatments with the exception of spring 2007. Irrigation treatments had significant effects on Ψ_{stem} during July, August and mean summer. While mean summer Ψ_{stem} in CON was -1.7 ± 0.4 MPa (-1.9 ± 0.4 MPa on day prior to irrigation), lower values were recorded in July in DI-J (-2.6 ± 0.7 MPa and -2.9 ± 0.6 MPa prior to irrigation) and DI-JA (-2.1 ± 0.6 MPa, -2.6 ± 0.5 MPa prior to irrigation), and in August in DI-A (-3.0 ± 0.7 MPa, -3.3 ± 0.6 MPa prior to irrigation) and DI-JA (-3.0 ± 0.7 MPa, -3.5 ± 0.4 MPa prior to irrigation).

Shoot growth

Shoot growth ceased on 12/07/07, 10/07/08 and 14/06/09, two weeks after irrigation treatments were

Table 1. Average relative extractable water (REW) to 0.8 m depth at 0.30 m from a drip emitter in a control (CON) and three deficit-irrigation treatments (DI-J, DI-A and DI-JA) in 2007, 2008 and 2009

	Spring	Summer			Autumn	Season
		July	August	Summer average		
2007						
CON	0.55^{c}	0.56^{b}	0.54^{a}	0.55^{a}	0.36	0.49^{c}
DI-J	0.74^{a}	0.48^{c}	0.51^{a}	0.50^{a}	0.36	0.56^{a}
DI-A	0.64^{b}	0.63^{a}	0.37^{b}	0.48^{a}	0.40	0.52^{b}
DI-JA	0.59^{bc}	0.45^{d}	0.31^{b}	0.37^{b}	0.32	0.44^{d}
2008						
CON	0.56	0.59^{a}	0.48^{a}	0.53^{a}	0.67^{a}	0.59^{a}
DI-J	0.57	0.28^{b}	0.46^{a}	0.39^{b}	0.58^{bc}	0.51^{c}
DI-A	0.54	0.62^{a}	0.26^{b}	0.40^{b}	0.63^{ab}	0.53^{b}
DI-JA	0.52	0.36^{b}	0.22^{b}	0.27^{c}	0.54^{c}	0.44^{d}
2009						
CON	0.55	0.61^{a}	0.64^{a}	0.63^{a}	0.59^{a}	0.58
DI-J	0.65	0.29^{b}	0.49^{b}	0.39^{b}	0.48^{d}	0.52
DI-A	0.57	0.65^{a}	0.23^{c}	0.44^{b}	0.56^{b}	0.53
DI-JA	0.54	0.30^{b}	0.20^{c}	0.25^{c}	0.53^{c}	0.45

Means within the same column followed by different letters are significantly different at $p < 0.05$, according to Duncan multiple range test.

commenced. Average seasonal shoot length in CON in the three seasons was 9.6 cm and no significant differences between treatments were found (Fig. 4), mainly due to high variability (mean CV = 179%). Shoot growth rate (per growing degree day) was significantly different on two dates (26/07/2007 and 10/07/2008) when

Table 2. Mean Ψ_{stem} in a control (CON) and three deficit-irrigation treatments (DI-J, DI-A and DI-JA) during 2007, 2008 and 2009 seasons

	Spring	Summer			Autumn	Season
		July	August	Summer average		
2007						
CON	–1.8	-1.7^{b}	-1.8^{a}	–1.8	–2.4	-2.0^{b}
DI-J	–1.1	-1.9^{b}	-1.8^{a}	–1.8	–2.5	-1.7^{a}
DI-A	–1.3	-1.3^{a}	-2.4^{b}	–2.0	–2.4	-1.8^{ab}
DI-JA	–1.1	-1.7^{b}	-2.5^{b}	–2.2	–2.6	-1.9^{ab}
2008						
CON	–1.8	-1.7^{a}	-1.9^{a}	-1.8^{a}	–1.5	–1.7
DI-J	–1.6	-2.9^{c}	-2.0^{a}	-2.3^{b}	–1.5	–1.8
DI-A	–1.7	-1.4^{a}	-3.2^{b}	-2.4^{bc}	–1.3	–1.8
DI-JA	–1.5	-2.2^{b}	-3.2^{b}	-2.8^{c}	–1.4	–1.9
2009						
CON	–1.7	-1.6^{ab}	-1.6^{a}	-1.6^{a}	–1.7	–1.7
DI-J	–1.3	-2.9^{c}	-1.8^{a}	-2.4^{ab}	–1.9	–1.8
DI-A	–1.5	-1.3^{a}	-3.4^{b}	-2.3^{ab}	–1.7	–1.8
DI-JA	–1.3	-2.6^{bc}	-3.4^{b}	-3.0^{b}	–1.5	–1.9

Means within the same column followed by different letters are significantly different at $p < 0.05$, according to Duncan multiple range test.

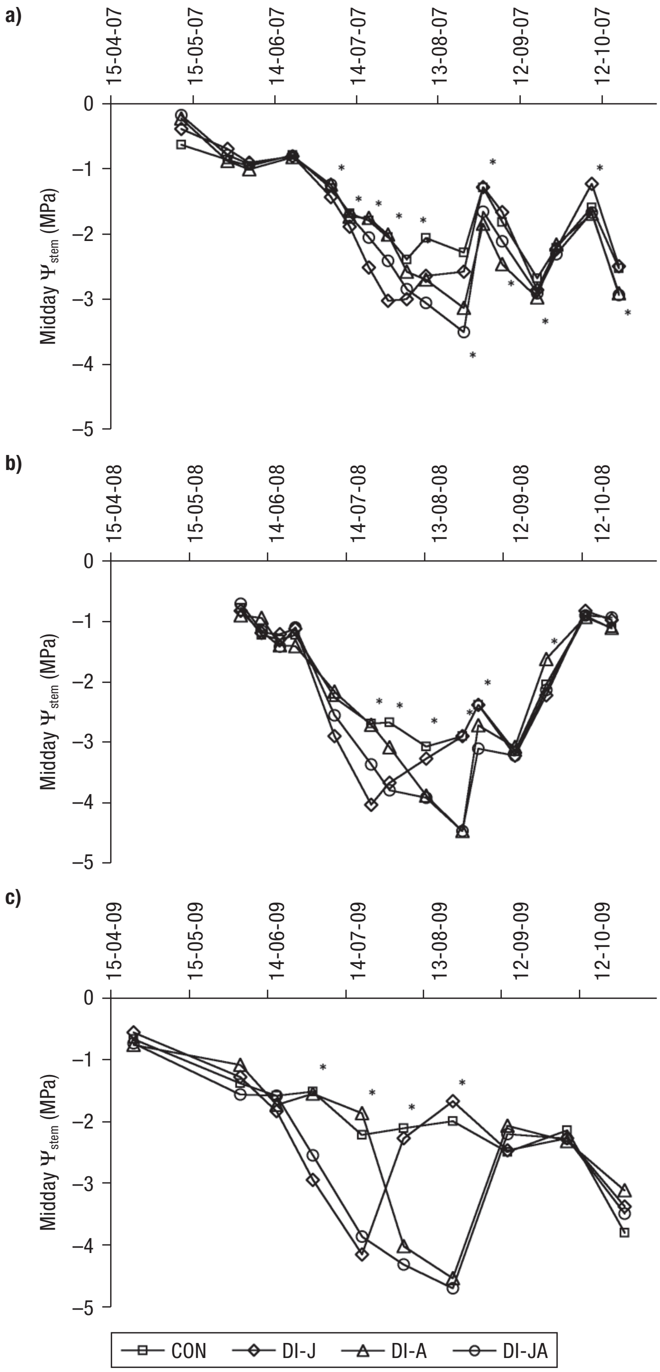

Figure 2. Evolution of midday Ψ_{stem} in a control (CON) and three deficit-irrigation treatments (DI-J, DI-A and DI-JA) in 2007 (a), 2008 (b) and 2009 (c). *, significant differences at $p < 0.05$. Values are means of 4 replicates.

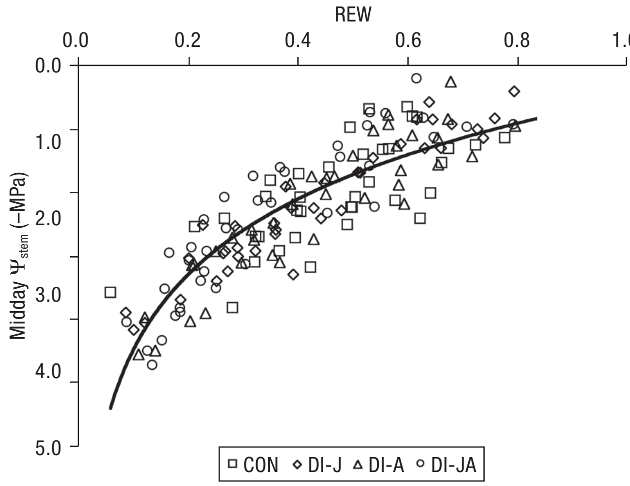

Figure 3. Relationship between midday $-\Psi_{stem}$ and REW in a control (CON) and three deficit-irrigation treatments (DI-J, DI-A and DI-JA). Regression: $y = -1.73 \ln(x) + 0.52$ ($R^2 = 0.77$).

shoots in CON grew significantly faster than in DI-JA. The fastest shoot growth (0.14 mm °d^{-1}) was recorded in June 2007. In that season, shoots were also longer than in the other years.

Shoot growth rate (y) during the main growth stage increased exponentially with increasing Ψ_{stem} (x) as $y = 0.32.e^{-1.22.x}$ ($R^2 = 0.76$) (Fig. 5). This relationship reveals that shoot growth would decrease by 30% and 50% of maximum at Ψ_{stem} of –1.0 and –1.3 MPa, respectively.

Fruit characteristics and oil production and their relationship with Ψ_{stem}

Large differences between years were observed in fruit characteristics at the end of the treatment period (late August-beginning of September) (Table 4) and oil production at harvest (Gómez-del-Campo, 2013). Olive dry weight and oil content in CON were higher in 2009 (0.46 g dw fruit^{-1} and 0.072 g oil fruit^{-1}) than in 2008 (0.30 g dw fruit^{-1} and 0.043 g oil fruit^{-1}, respectively).

Fruit characteristics (olive dry weight and oil content), responded to irrigation in the 2008 and 2009 seasons (Table 4). Fruit dry weight and fruit oil content (g fruit^{-1}) were higher in CON compared with DI-JA. Fruit dry weight and oil content (g fruit^{-1}) at the end of the experimental period were 60 and 20% of the value at harvest, respectively.

Fruit dry matter and oil content (g fruit^{-1}) were linearly related to mean summer Ψ_{stem} at the end of the experimental period ($R^2 > 0.73$) and at harvest ($R^2 > 0.51$) (data not shown).

Across all treatments, oil production (expressed as % of CON) was highly related with Ψ_{stem} in August (Fig. 6).

Table 3. Mean Ψ_{stem} prior to irrigation in a control (CON) and three deficit-irrigation treatments (DI-J, DI-A and DI-JA) in 2007, 2008 and 2009

	Spring	Summer			Autumn	Season
		July	August	Summer average		
2007						
CON	–1.8	-2.0^{b}	-2.0^{a}	-2.0^{a}	–2.3	-2.0^{a}
DI-J	–1.1	-2.1^{b}	-2.1^{a}	-2.1^{a}	–2.4	-2.0^{a}
DI-A	–1.4	-1.7^{a}	-2.7^{b}	-2.3^{ab}	–2.3	-2.2^{a}
DI-JA	–1.2	-2.1^{b}	-3.0^{b}	-2.7^{b}	–2.6	-2.4^{b}
2008						
CON	–1.9	-1.9^{a}	-2.2^{a}	-2.1^{a}	–1.8	-2.0^{a}
DI-J	–1.7	-3.1^{c}	-2.7^{a}	-2.8^{b}	–2.2	-2.4^{bc}
DI-A	–1.9	-1.8^{a}	-3.5^{b}	-2.8^{b}	–1.9	-2.3^{b}
DI-JA	–1.7	-2.6^{b}	-3.8^{b}	-3.3^{b}	–2.2	-2.6^{c}
2009						
CON	–1.9	-1.7^{a}	-1.7^{a}	-1.7^{a}	–1.7	–1.7
DI-J	–1.6	-3.4^{b}	-2.2^{a}	-2.8^{b}	–1.9	–2.3
DI-A	–1.9	-1.6^{a}	-3.6^{b}	-2.6^{b}	–1.8	–2.2
DI-JA	–1.7	-3.0^{b}	-3.8^{b}	-3.4^{b}	–1.5	–2.5

Means within the same column followed by different letters are significantly different at $p < 0.05$, according to Duncan multiple range test.

No significant relationships were found between oil production and Ψ_{stem} in July or mean values recorded during summer (not shown). A tighter regression was obtained between oil production and mean Ψ_{stem} values ($R^2 = 0.75$) than with Ψ_{stem} the day prior to irrigation ($R^2 = 0.70$). Oil production was reduced by 10% at Ψ_{stem} values of –2.3 and –2.8 MPa for mean and prior to irrigation and by 20% at values of –3.3 and –3.8 MPa, respectively.

Table 4. Fruit characteristics at the end of treatment periods in a control (CON) and three deficit-irrigation treatments (DI-J, DI-A and DI-JA) in 2007, 2008 and 2009

	Olive dry (g fruit^{-1})	Oil content	
		(% dry weight)	(g fruit^{-1})
2007			
CON	0.36^{a}	14.12^{a}	0.050
DI-J	0.31^{c}	13.26^{ab}	0.042
DI-A	0.34^{b}	11.64^{b}	0.040
DI-JA	0.34^{b}	12.91^{ab}	0.044
2008			
CON	0.30^{a}	14.02	0.043^{a}
DI-J	0.25^{c}	13.84	0.034^{b}
DI-A	0.27^{b}	11.45	0.031^{c}
DI-JA	0.21^{d}	11.00	0.023^{d}
2009			
CON	0.46^{a}	15.12^{a}	0.072^{a}
DI-J	0.33^{b}	11.29^{c}	0.037^{b}
DI-A	0.39^{ab}	14.20^{ab}	0.056^{ab}
DI-JA	0.33^{b}	12.72^{bc}	0.041^{b}

Means within the same column followed by different letters are significantly different at $p < 0.05$, according to Duncan multiple range test.

Discussion

The strategy that growers chose for irrigation management depends on orchard characteristics. An irrigation regime that ensures high plant water status throughout the season by applying water to support crop evapotranspiration is appropriate for young olive trees, where maximum growth is required for orchard establishment (Pérez-López *et al.,* 2007; Gómez-del-Campo *et al.,* 2008). This strategy is not, however, the most profitable in many mature olive orchards. RDI applied from around the end of fruit drop until the start of oil synthesis can save water with small loss of production (Goldhamer, 1999; Alegre *et al.,* 2002). For this, appropriate timing, duration and intensity of water deficit must be defined. In this experiment threshold values for Ψ_{stem} were obtained for the following periods: shoot growth (June in the experimental condi-

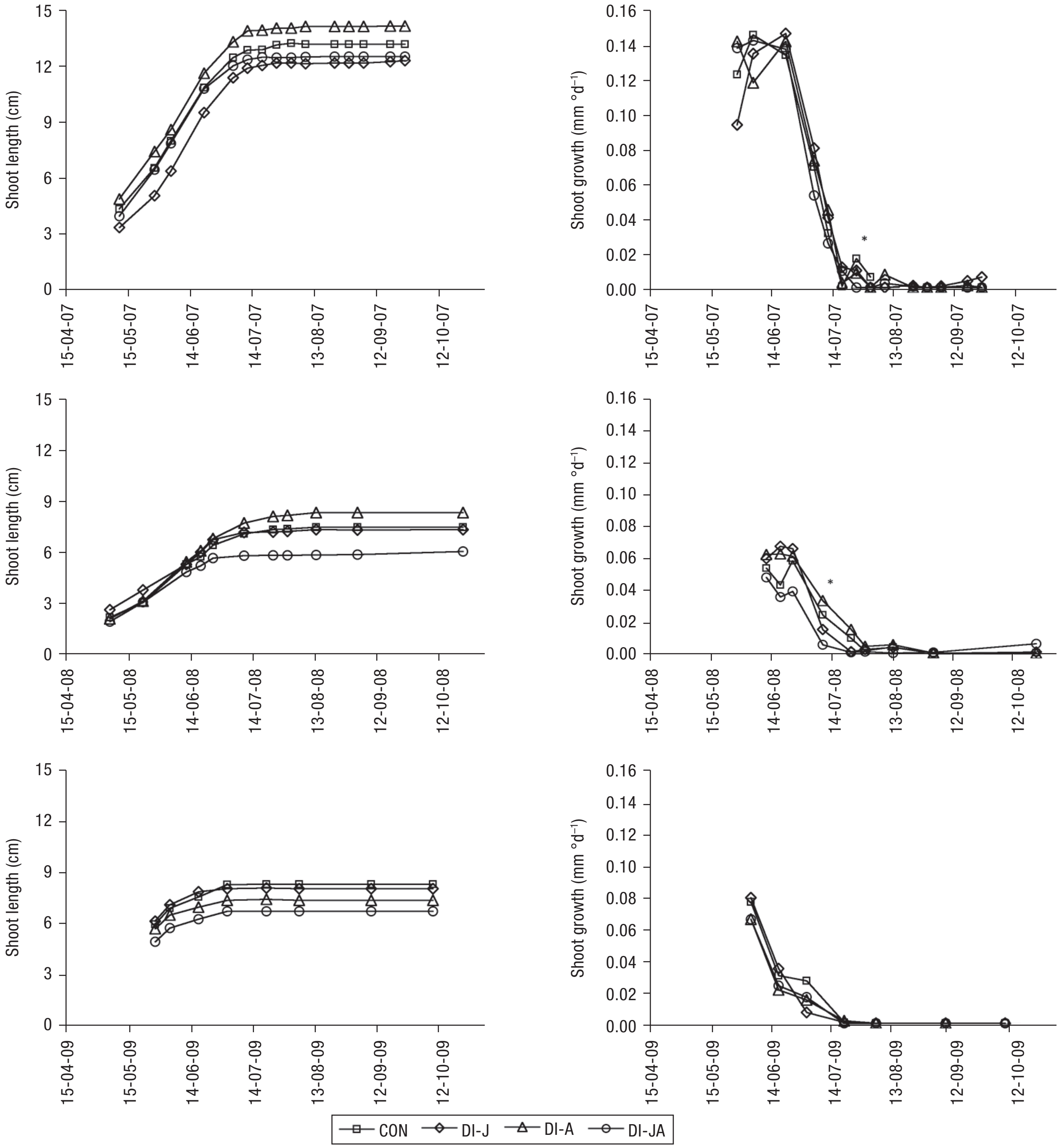

Figure 4. Evolution of shoot length (cm) and growth (mm per growing degree day) in a control (CON) and three deficit-irrigation treatments (DI-J, DI-A and DI-JA). * Significant differences at $p<0.05$. Values are means of 24 replicates.

tions), final fruit drop until mid-summer (July) and mid-summer until start of oil synthesis (August).

Ψ_{stem} values depend on the experimental conditions. Hedgerow canopy and soil characteristics (effective rooting depth of 0.60 m) and hot, dry summer caused a high water stress with Ψ_{stem} falling to –4.7 MPa (Fig. 2), comparable with rainfed olives (Moriana *et al.*, 2003; Tognetti *et al.*, 2006). The hedgerow orchard had high leaf area intercepting radiation (Connor & Gómez-del-Campo, 2013) this will increase water

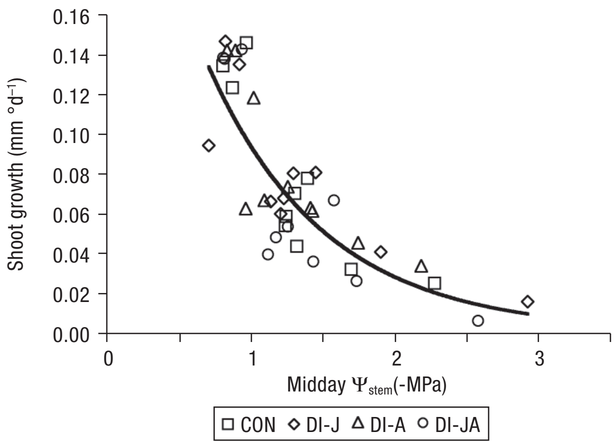

Figure 5. Relationship between shoot growth (mm per growing degree day) and Ψ_{stem} (-MPa) prior to irrigation in a control (CON) and three deficit-irrigation treatments (DI-J, DI-A and DI-JA). Regression: $y = 0.32\ e^{-1.22x}$ ($R^2 = 0.76$).

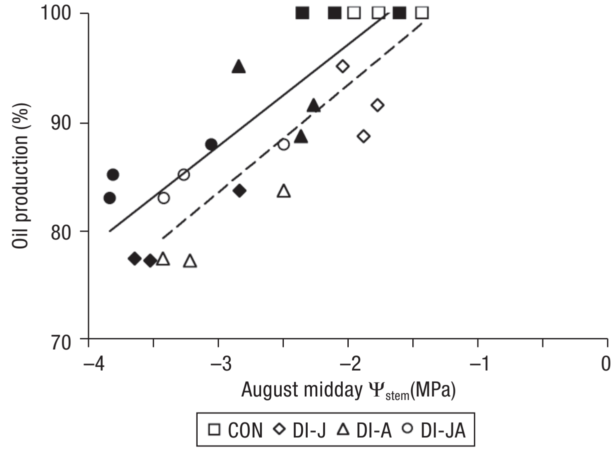

Figure 6. Relationship between oil production relative to control (CON) and August Ψ_{stem}. Regression for mean Ψ_{stem} (open symbols): $y = 10.2x + 114$ ($R^2 = 0.75$). Regression for Ψ_{stem} prior to irrigation (solid symbols): $y = 9.2x + 115$ ($R^2 = 0.70$).

transpiration and reduce Ψ_{stem} compared with other canopy shapes with lower leaf area (Shackel *et al.*, 1997; Naor, 2006), as in traditional olive orchards trained in vase.

High oil production and high evaporative demand conditions avoided excessive vegetative growth restricted to spring (mean shoot length of 9.6 cm, Fig. 4). In this experiment crop load did not affect Ψ_{stem} (Gucci *et al.*, 2007; Trentacoste *et al.*, 2011) because fruit number was not significantly modified by irrigation treatments (Gómez-del-Campo, 2013).

In this experiment, a decrease in shoot growth by over 50% was obtained when irrigation was applied at a Ψ_{stem} lower than –1.3 MPa. Grattan *et al.* (2006) observed significant decrease in shoot growth when Ψ_{stem} was below –1.5 MPa at the beginning of July. Shoot growth was significantly reduced when Moriana *et al.* (2012) irrigated at Ψ_{stem} of –2.0 MPa, but not at –1.2 MPa in both 'Cornicabra' and 'Morisca' experiments. Meanwhile the response of shoot growth of young trees differs to productive ones. Growth of youth trees was reduced in 50% at Ψ_{stem} of –1.8 MPa (Gómez-del-Campo *et al.*, 2008), perhaps because of the low competition for water between shoots (few shoots) and fruits. Different irrigation strategies during shoot growth periods are appropriate depending on orchard vigour due to the high impact of irrigation on shoot growth in olive (Sofo *et al.,* 2008). The challenge in hedgerow management is to control vegetative vigor, and geometrical characteristics to maximize productivity and allow access for harvesting machines (Connor & Gómez-del-Campo, 2013). However, care must be taken when deficit irrigation is applied during this period because shoot growth occurs at the same time as flowering, fruit set and fruit drop, so production could be reduced if deficit irrigation is applied early in this phase.

Although irrigation treatments were applied before less than 20% of final oil content had been accumulated at the beginning of September, they produced significant differences in fruit dry matter and oil content at the end of the experimental period and at harvest (g fruit^{-1}) (Table 4 and Gómez-del-Campo, 2013) as in other experiments (Moriana *et al.,* 2003; Gucci *et al.,* 2007). Meanwhile the impact in oil production depended on the summer period when deficit was applied. Early summer deficit from the end of fruit drop until mid-summer (DI-J), that irrigation was applied during this month at mean Ψ_{stem} of -2.9 ± 0.6 MPa, had no significant effect on oil production in any experimental year and no significant relationship was obtained with Ψ_{stem}. Similar responses have been reported by Goldhamer (1999) and Lavee *et al.* (2007). By contrast, deficit irrigation applied from mid-summer until start of oil synthesis (August) was shown to be unprofitable and irrigation should be applied at Ψ_{stem} higher than –2.0 MPa as in treatment CON. Oil production decreased linearly as irrigation was applied at lower Ψ_{stem} in August (Fig. 6). Moriana *et al.* (2012) used –2.0 MPa throughout the season as threshold value in young 'Cornicabra' in Ciudad Real and 'Morisca' in Badajoz. They found that production was affected in 'Cornicabra' but not in 'Morisca'.

The data of this experiment give some information for possible Ψ_{stem} threshold values for irrigation of mature 'Arbequina' orchards. During shoot growth period (June in the experimental conditions), Ψ_{stem} should be maintained higher than –1.0 MPa if high shoot growth is desired, but if shoot growth is to be reduced to more than half of the maximum, irrigation should be applied below –1.3 MPa. From the end of fruit drop until mid summer (July) water can be saved in this experiment by irrigating at Ψ_{stem} of –2.9 MPa but Ψ_{stem} should be maintained higher than –2.0 MPa later in August to prevent decrease of oil production. It should be noted that the response of growth and oil production to water potential is genetically controlled (Tognetti *et al.*, 2006), that crop loads and climatic conditions will also determine the threshold values for irrigation (Naor, 2006; Moriana *et al.*, 2012) and that experiments with other cultivars and growing conditions are necessary to determine individual threshold values.

The advantage of Ψ_{stem} measurements for irrigation management lays in ability to integrate soil, climatic and crop conditions such that threshold values have more general application, *i.e.* they are not restricted, as are threshold values of soil water status, to individual sites. They do, however, have disadvantages. While Ψ_{stem} threshold values indicate when irrigation should start, they do not indicate how long irrigation should last. This can be overcome by placing soil water sensors at drainage depth to record when effective root depth is wetted. A more serious disadvantage is that Ψ_{stem} cannot be monitored automatically. Until that is possible, relationships between soil water content and Ψ_{stem}, as determined here, must be used. Analysis of data revealed that Ψ_{stem} was highly correlated to REW ($R^2 = 0.77$) (Fig. 3). Similar responses of Ψ_{stem} to soil moisture content have been reported in olive (Moriana *et al.,* 2002; Gómez-del-Campo *et al.,* 2008). Better correlation was obtained for each treatment separately indicating that this relationship is site-specific. Tree water status nor only depends on the water measured by the nearby sensors, sensor location in relation to emitter, soil characteristics and root development in the surrounding soil and water movement inside the tree will determine its hydration capacity.

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