Irrig Sci (2016) 34:313–325
DOI 10.1007/s00271-016-0505-9

ORIGINAL PAPER

Effects of different irrigation regimes on a super-high-density olive grove cv. "Arbequina": vegetative growth, productivity and polyphenol content of the oil

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Received: 6 June 2014 / Accepted: 8 March 2016 / Published online: 26 April 2016

Abstract The effects of multiple irrigation regimes on the relationships among tree water status, vegetative growth and productivity within a super-high-density (SHD) "Arbequina" olive grove (1950 tree/ha) were studied for three seasons (2008–2010). Five different irrigation levels calculated as percentage of crop irrigation requirement using FAO procedures (Allen et al. in Crop evapotranspiration. Guidelines for computing crop water requirements. Irrigation and drainage paper 56. FAO, Rome, 1998) were imposed during the growing season. Periodically during the growing season, daytime stem water potential (Ψ_{STEM}), inflorescences per branch, fruits per inflorescence and shoot absolute growth rate were measured. Crop yield, fruit average fresh weight and oil polyphenol content were measured after harvest. The midday Ψ_{STEM} ranged from −7 to −1.5 MPa and correlated well enough with yield efficiency, crop density and fruit fresh weight to demonstrate its utility as a precise method for determining water status in SHD olive orchards. The relationships between midday Ψ_{STEM} and the horticultural parameters suggest maintaining Ψ_{STEM} values between −3.5 and −2.5 MPa is optimal for moderate annual yields of good quality oil. Values below −3.5 MPa reduced current season productivity, while values over −2.5 MPa were less effective in increasing productivity, reduced oil quality and produced excessive crop set that strongly affected vegetative growth and fruit production the following season. On the basis of the result given here, irrigation scheduling in the new SHD orchards should be planned on a 2-year basis and corrected annually based on crop load. Collectively, these results suggest that deficit irrigation management is a viable strategy for SHD olive orchards.

Communicated by A. Naor.

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Introduction

The olive (*Olea europaea* L.) is extensively cultivated in the arid and semiarid Mediterranean basin regions characterized by limited water availability and high evaporative demand. This evergreen species, due to its ability to resist drought, has traditionally been grown under rainfed conditions in low-density groves. Low densities maximize the availability of stored soil water per tree compared to higher densities (Connor and Fereres 2005; Fernández and Moreno 1999; Gimenez et al. 1997; Lo Gullo and Salleo 1988). Under rainfed conditions, olives generally have reduced photosynthetic rates that limit growth and yield (Bongi and Palliotti 1994).

Recent demonstrations of olive oil's health benefits have increased demand for olive oil. To fill this demand, many traditional, rainfed olive groves are being converted to irrigation (Orgaz and Fereres 1997) and new orchards are being planted at super-high density (SHD) up to 2500 trees/ha (Tous et al. 2010).

The SHD olive groves were first planted in the 1990s. Their specific cultivars were low-vigor, early bearing and self-fertile with high yield efficiencies, tolerant of fungal diseases and had thin and flexible 1-year-old shoots and a canopy architecture suitable for mechanical harvesting (Tous et al. 2008; Vossen 2007) with straddle harvesters. This management system significantly reduces production costs by decreasing the hand labor required for pruning and harvesting. However, the system also requires specialized management techniques (Vossen 2002). Irrigation is a particularly important component in SHD orchards as the trees have a limited size of the root zone, a high leaf area index and, as a consequence, high water demands (Connor 2005; Cuevas et al. 2013).

In traditional, low-density olive orchards, irrigation is essential for oil quality and quantity (Girona 1996; Goldhamer et al. 1994; Lavee et al. 1990; Moriana et al. 2003; Samish and Spiegel 1961).

Both young (Grattan et al. 2006) and mature (Fernández et al. 2013; Naor et al. 2013) SHD olive orchards responded positively to irrigation, while water stress decreased shoot growth (Gómez-del-Campo et al. 2008, Gómez-del-Campo 2013a) and therefore productivity. Optimal irrigation volume in young SHD olives was found to be ~75 % of ET_c (Grattan et al. 2006). A reduction in water use up to 16 % applied in July did not affect oil production (Gómez-del-Campo 2013a), while a reduction of 72 % of the irrigation water resulted in 26 % oil yield loss (Fernández et al. 2013).

High irrigation rates are associated with decreased oil quality (Berenguer et al. 2006; Ben-Gal et al. 2008; Dag et al. 2008). Collectively, these earlier studies suggest moderate water stress results in maximum yields of high-quality oil while limiting vegetative growth.

Optimal irrigation regime is required in SHD orchards because tree size must be controlled for mechanical harvesting and it is necessary to maintain high-quality oil. “Arbequina” oil is known to have a polyphenol content that is already low, and excessive water application can cause a further reduction in the antioxidant component of the oil (Berenguer et al. 2006; Gucci et al. 2004; Gucci and Servili 2006; Patumi et al. 2002).

Correct irrigation scheduling for SHD orchards should be based on plant water status and drought stress level threshold values. Stem water potential (Ψ_{STEM}) measurements are an accurate method of determining plant water status and therefore could be used to adjust irrigations scheduled on the basis of the water balance as this is strongly influenced by orchard characteristics (Hsiao 1990; Jones 2004; McCutchan and Shackel 1992; Shackel et al. 1997; Naor 2006).

Olive leaves lose turgor at a leaf water potential of −3.5 MPa (Dichio et al. 2003; Lo Gullo and Salleo 1988; Rieger 1995). Although loss of turgor compromises cell metabolism (Chaves et al. 2003), olive leaves can tolerate Ψ_{STEMs} as low as −8 MPa (Moriana et al. 2003; Xiloyannis et al. 1988). The xylem water columns of olive trees can withstand the high tensions that develop during droughts (Connor 2005) with or without limited embolization (Cochard et al. 1992, 1994; Salleo and Lo Gullo 1993; Sperry and Tyree 1988).

In light of this, we conducted a 3-year trial that evaluated the response of a SHD “Arbequina” orchard to different irrigation levels. The relationships among irrigation, tree water status, vegetative growth, tree productivity and oil polyphenol content were evaluated. The objective was to determine the optimal stem water potential thresholds for simultaneously decreasing water use while maintaining productivity and improving the oil polyphenol content.

Materials and methods

Experimental orchard and environmental conditions

A 3-year study (2008–2010) was carried out in a commercial 4-year-old “Arbequina” grove, established in 2004 in Sicily (Italy) (37°46′28″N, 12°30′19″ E, 12 m above sea level). Trees were spaced 1.5 × 3.5 m (about 1905 trees/ha).

The soil at the experimental site was composed by 52 % of sand, 26 % of silt and 22 % of clay with a pH of 7.7 and 1.32 % of organic matter.

The climate was Mediterranean, characterized by rainfall (Fig. 1a) from October to April and dry from May to September with a mean annual rainfall of 474 mm (30-year average, 1965–1994). Maximum monthly temperatures began to increase in May and reached the peak of 37 °C in 2008, 38 °C in 2009 and 34 °C in 2010. Minimum monthly temperatures followed the same yearly pattern as the maximum temperatures, but the values, on average, were found to be 15 °C lower (Fig. 1b).

Irrigation treatments and experimental design

The irrigation treatments were determined using the FAO-CROPWAT 8.0 model (FAO 1992), based on the recommended FAO procedure (Allen et al. 1998). The model calculates crop irrigation requirements (CIR) using local minimum and maximum temperatures, wind speed, humidity, daily sun hours and precipitation. This program uses the FAO (FAO 1998) Penman–Monteith equation for the calculation of the reference evapotranspiration (ET_0). Thirty-year average climatic and rainfall data were provided by a public weather station, Servizio Informativo Agrometeorologico Siciliano (SIAS), located 5 km from the orchard.

The daily reference crop evapotranspiration (ET_o) was then used to calculate the crop evapotranspiration as follows:

$$ET_c = ET_0 \times K_c \times K_r,$$

where the crop coefficient (K_c) was obtained from the literature (Allen et al. 1998; Fernández et al. 2006; Orgaz et al. 2005; Testi et al. 2004) and varies with the phenological stage

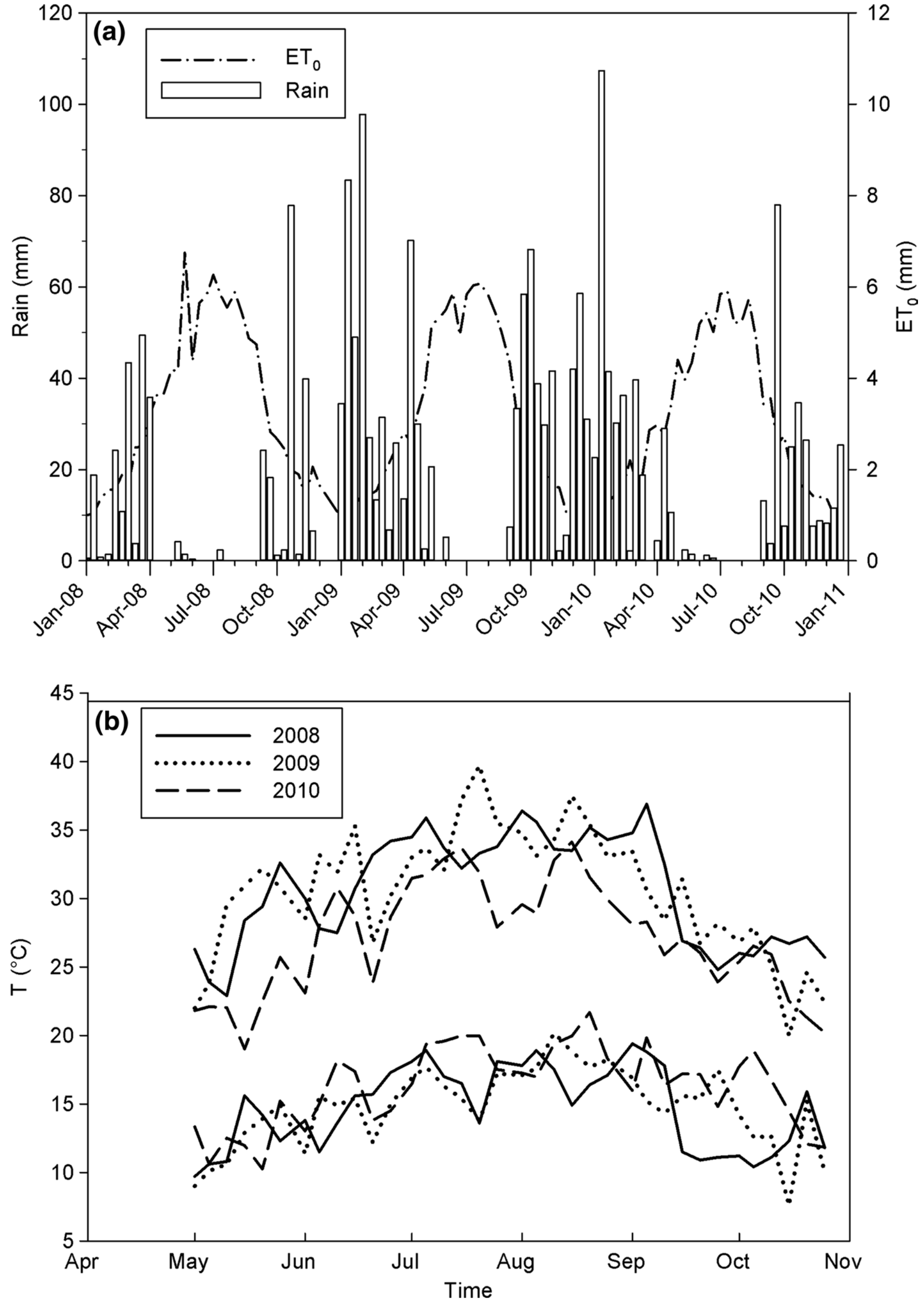

Fig. 1 Daily reference evapotranspiration rate (ET_0, mm) and daily cumulative precipitation (mm) from January 2008 to December 2010 (**a**), and 5 days mean of minimum and maximum air temperatures (°C) for three experimental growing seasons (from May to October) (**b**) recorded at the weather station in Marsala (west Sicily)

of the crop (0.34 in May, from 0.43 to 0.72 in June, 0.75 in July, August and September, from 0.63 to 0.37 in October), while the reduction coefficient (K_r) that takes into account the fraction of ground covered by the crop (Fereres and Castel 1981; Grattan et al. 2006), was calculated from direct measurements of shaded soil at midday and resulted 0.58.

The crop irrigation requirement, on a 10-day basis, was calculated as follows:

$$CIR = ETc - P_e.$$

The effective rainfall, P_e, is the rainfall available to the trees calculated using the USDA Natural Resources Conservation Service (NRCS) methodology (Obreza and Pitts 2002; USDA 1970).

In 2008, five irrigation treatments were tested: 100, 75, 50, or 25 % of CIR and a non-irrigated "rainfed" control. To avoid irreversible water stress, the "rainfed" controls received a minimal irrigation during the warmer and drier months.

In 2009, the experiment was repeated and the quantities of water supplied were slightly reduced based on the previous year's results. In 2010, a malfunctioning irrigation system compromised 75 % CIR treatment and decreased irrigation in the other treatments by 50 %.

The experiment was laid out in a randomized complete block design with five blocks, each consisting of 45 trees (nine trees per treatment forming a plot of three adjacent rows of three trees each). The central tree from each irrigation plot was used for data collection. The actual amount of water applied was presented as the percentage of the annual CIR.

Water was supplied by three self-compensating in-line drippers per plant spaced at 50 cm intervals delivering 1.6 l/h each. Solenoid valves regulated the different watering regimes and were automatically operated by a controller (Hit Logic 2-Hit Product Corporation, Lindsay, CA). The applied water was measured using a mechanical water meter installed at the head of each irrigation treatment.

Measurements

Water potential

In 2008 and 2009, the stem water potential (Ψ_{STEM}) was measured at 3-h intervals, from dawn to dusk, using a pressure chamber (PMS Instrument Co., Corvallis-Oregon). Shoots of the current year's growth with five or six pairs of fully expanded leaves were selected from the mid-canopy and then covered with plastic envelopes and aluminum reflective foils for at least 1 h before measurement in order to reduce leaf transpiration (Begg and Turner 1970) and equilibrate with branch xylem water potential. Shoots were then detached, and Ψ_{STEM} measurements were performed on one shoot from each of five trees from each irrigation treatment. Pre-dawn Ψ_{STEM} measurements were performed between 3:30 am and sunrise, and midday Ψ_{STEM} was measured between 12:30 and 1:30 pm on 4 September and 9 October 2008, and on 11 August and 1 September 2009. On the 4th of September 2008, no pre-dawn measurements were taken. In 2010, midday Ψ_{STEM} measurements were taken weekly from 13 July to 27 September.

Vegetative growth

To determine the trunk cross-sectional area (TCSA), trunk circumference was measured at 10 cm above the ground. Shoot growth was monitored by measuring the shoot length of four randomly preselected shoots, two on each side of the hedgerow, per each replicate tree. Measurements were taken weekly from August until harvest in 2008 and every 10 days starting 27 April in 2009. Shoot length measurements in 2010 were taken every 2 weeks, starting at the end of March and ending on 28 September. The daily average shoot growth rate (SGR), between two successive measurement days, was calculated as given below (McGraw and Garbutt 1990):

$$\text{SGR} = \frac{(L_2 - L_1)}{(t_2 - t_1)} \text{ cm/day;}$$

where L_1 and L_2 are shoot length at times t_1 and t_2.

During both winters (2008–2009 and 2009–2010), the weight of pruned material was recorded for each tagged tree.

Productive parameters

On the same shoots used to monitor vegetative growth, the number of inflorescences per branch was determined at full bloom. The number of fruits per inflorescence and per shoot was recorded at 31 days after full bloom in 2009 and at 28 days after full bloom in 2010.

The trees were harvested on 15 October 2008, 26 October 2009 and 24 October 2010, and the yield per tree was weighed; a sample of 30 fruits per plant was collected to calculate the average fruit weight. Yield efficiency (YE = kg of fruit/TCSA) and crop density (CD = number of fruit/TCSA) (Lombard et al. 1988) were calculated.

Oil was extracted immediately after harvest using a continuous system (VITONE ECO Srl, Bitonto, Italy) located inside the orchard. Fruits were first washed and then crushed by a hammer mill. The resulting olive paste was mixed at 25 °C for 20 min, and the oil was separated by three-phase centrifuge. Since the minimum quantity of fruits that this machine can process is 80 kg, fruits from the same irrigation treatments across all blocks were mixed. These were used to determine the percentage of oil and then calculate oil yield (t/ha). The oil was filtered and stored in the dark at 8 °C until analysis for total polyphenol (Singleton and Rossi 1965).

The effects of irrigation were analyzed by one-way analysis of variance (ANOVA) using Systat package (SYSTAT Software Inc., Chicago, IL). Differences between treatments were determined by the Tukey test. Average yearly data were statistically compared by the Student's *t* test. Statistical significance was set at $p \leq 0.05$.

Results

Environmental conditions

The high evapotranspiration rate observed during summer months accompanied by an absence of rainfall (Fig. 1a) created a meaningful water deficit. Spring 2008 was particularly dry with only 36 mm of rainfall in April and 7 mm in May, followed by a 6-month period without rains >2 mm (the minimum below it is not contributes to irrigation), from the first week of April to the second week of

Table 1 Cumulative seasonal irrigation and actual seasonal average of the percentage of estimated crop irrigation requirement (CIR, mm) (Allen et al. 1998) in each treatment for five irrigation treatments in 2008, 2009 and 2010

2008		2009		2010	
Cumulative irrigation (mm)	% of CIR	Cumulative irrigation (mm)	% of CIR	Cumulative irrigation (mm)	% of CIR
6	3	34	16	18	8
77	32	44	21	61	25
126	51	87	41	77	35
160	65	132	62	–	–
247	100	176	83	111	50

The irrigation periods were from 22 June to 14 October 2008, 07 July to 13 September 2009 and 30 June to 4 September 2010

September. In 2009, the dry season was delayed until mid-May; precipitations >2 mm did not occur until the first week of June (5.2 mm of rain) and then again in the second week of September (6.4 mm of rain). In 2010, the dry season commenced and ended earlier than in previous years, from the fourth week of April to the second week of September.

The beginning and the end of the irrigation periods (from 22 June to 14 October 2008, 07 July to 13 September 2009 and 30 June to 4 September 2010) reflected the different trends in rainfall of three seasons.

In 2008 the cumulative ET_c was 310 mm, P_e was 109 mm, and CIR was 245 mm. In 2009 ET_c was 305 mm, P_e was 205 mm, and CIR was 212 mm. In 2010 ET_c was 288 mm, P_e was 140 mm, and CIR was 221 mm. The actual irrigation treatments were 100, 65, 51, 32, 3 % of CIR in 2008, 83, 62, 41, 21, 16 % of CIR in 2009 and 50, 35, 28, 18 % of CIR in 2010 (Table 1).

Tree water potential

The Ψ_{STEM} values in 2008 and 2009 decreased progressively during the day for all treatments (Fig. 2), reaching their lowest values between midday and 04:00 pm. In 2008, the Ψ_{STEM} was first recorded during the first week of September before the autumn rainfall; the dry climatic conditions (no rainfall >2 mm) that persisted for 153 days induced a severe water deficit (Fig. 2a). The lowest Ψ_{STEM} values were found in "rainfed" plants (around −6.5 MPa) and in plants irrigated with 32 % of CIR (−5 MPa). Water stress levels were significantly lower in two highest irrigation treatments (greater than −3 MPa). Intermediate values (−4 MPa) were recorded in plants that received 51 % of CIR. An increase in Ψ_{STEM} was observed for all treatments in October 2008 (Fig. 2b) due to abundant rainfall (43 mm) and a dramatic decrease in ET_0 in the second half of September (Fig. 1a). Trees that were irrigated with 100, 65 and 51 % of CIR recovered their water status completely, showing similar pre-dawn Ψ_{STEM} values (above −1 MPa) and midday Ψ_{STEM} values close to −1 MPa. Stem water potentials of non-irrigated trees differed significantly from the other treatments for both pre-dawn (−2 MPa) and midday (−4 MPa) measurements, showing a lack of full water potential recovery following the autumnal rainfall.

In 2009, the first Ψ_{STEM} measurements were taken at the beginning of the second week of August, following a 71-day period of drought and a wet spring (Fig. 2c). Trees supplied with irrigation equivalent to 83, 62 and 41 % of CIR showed nonsignificant differences in Ψ_{STEM} ranging from −0.5 (pre-dawn) to −1.9 MPa (midday). Lower Ψ_{STEM} values were observed in two lowest irrigation treatments; they had midday Ψ_{STEM} of −3.9 MPa for 21 % treatment and −5.2 MPa for 16 % treatment.

At the beginning of September, after a dry period of 92 days, plants were more stressed (Fig. 2d) than during previous measurements. The plants irrigated with 16, 21 and 41 % of CIR showed pre-dawn Ψ_{STEM} of −5, −4 and −2 MPa, respectively, and midday Ψ_{STEM} of −6, −5 and −4 MPa, respectively. Ψ_{STEM} for two highest irrigation treatments was −0.5 MPa, for pre-dawn measurement and −2 MPa, at midday. Midday Ψ_{STEM} values of the most stressed date of measurement (153, 92 and 121 days without rain in 2008, 2009 and 2010, respectively) increased with increasing irrigation level (Fig. 3a; $r^2 = 0.65$, $p < 0.001$). Specifically, a steep reduction in midday Ψ_{STEM} (from −3.5 to −6.5 MPa) was observed for CIR under 50 %, while higher water applications were less effective in increasing midday Ψ_{STEM}.

Yield

Fruit yield was improved by irrigation in 2008 and 2009 (Table 2). In 2008, supplying 51 % of CIR increased yield by 60 % compared to "rainfed" trees. However, additional water did not further increase production. The highest percentage of oil and polyphenol content were produced by 32 % of CIR treatment. Highest irrigation levels negatively affected these parameters.

In 2009, 16, 21 and 41 % of CIR treatments produced 8−10 t/ha and 62 % and 83 % CIR treatments

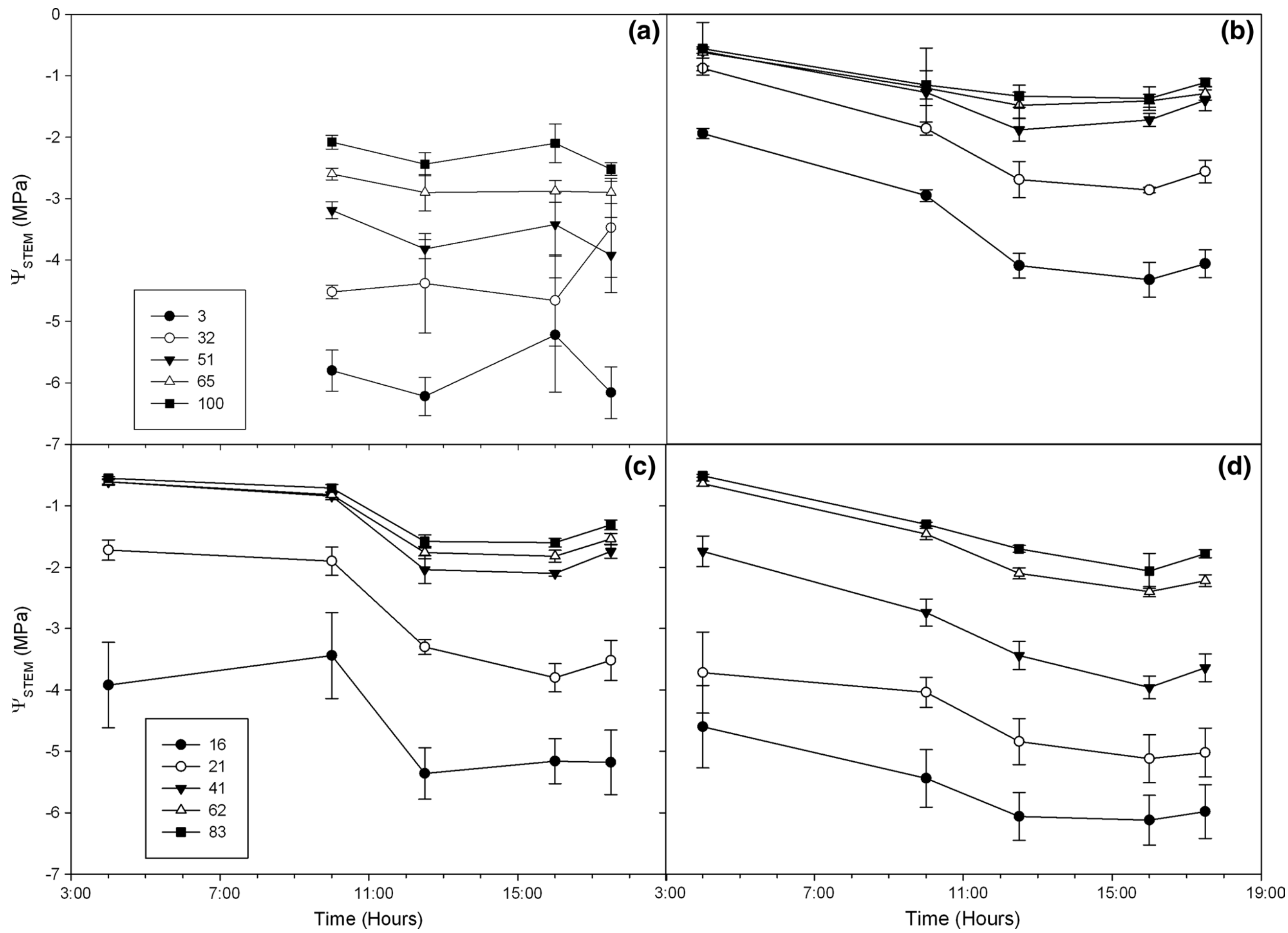

Fig. 2 Daily time course of the stem water potential (Ψ_{STEM}, MPa) on 04 September 2008 (**a**), 09 October 2008 (**b**), 11 August 2009 (**c**) and 01 September 2009 (**d**) in five irrigation treatments (CIR, %). The *vertical bars* represent two standard errors of the mean of five measurements taken in each treatment

produced ~14 t/ha. Fruit number per tree increased from 3000 to over 6000 fruits/tree for CIR above 41 %. The 2009 crop yield was significantly higher ($p \leq 0.01$) than 2008.

The highest oil percentages in 2009 were produced by 41 % of CIR treatment. Additional water negatively affected this parameter. The polyphenol content of the oils (Table 2) was negatively affected by irrigation, decreasing linearly from 175 to 48 mg/kg. Oil yield increased from 1.1 t/ha in the lowest irrigation treatment to a mean of 2 t/ha in two highest treatments.

In 2010, due to a malfunctioning of the irrigation system the volumes applied never exceeded 50 % of CIR. Irrigation did not affect any productivity parameter except polyphenol content. The highest oil polyphenol content was from 28 % of CIR treatment. Relative to 2008 and 2009, the 2010 crop yield per ha and fruit number per tree were significantly lower and the fruit had a higher percentage of oil with higher polyphenol levels.

Because the significant TCSA increases observed from 2008 to 2010 were not correlated with irrigation water (Table 2), we calculated yield efficiency (YE) to account for the variability in tree size.

Yield efficiency was positively influenced by irrigation level only in 2008 and 2009, while no effect was observed in 2010 (Table 2). Specifically, the 2008 yield efficiency increased from 0.08 kg/cm^2 in the lowest irrigation treatment to 0.20 kg/cm^2 in the highest irrigation treatment. In 2009 16, 21 and 41 % of CIR treatments had a significantly lower yield efficiency (about 0.14 kg/cm^2) compared to two highest irrigation treatments (0.22 kg/cm^2). No statistically significant differences were found in yield efficiency between 2008 and 2009 (Table 2), but the yield efficiency was found to be significantly lower in 2010. The pooled data for 2008 and 2009 showed a nonlinear relationship between YE and % CIR, indicating similar response in both years (Fig. 3b). Furthermore, the pooled 2008 and 2009

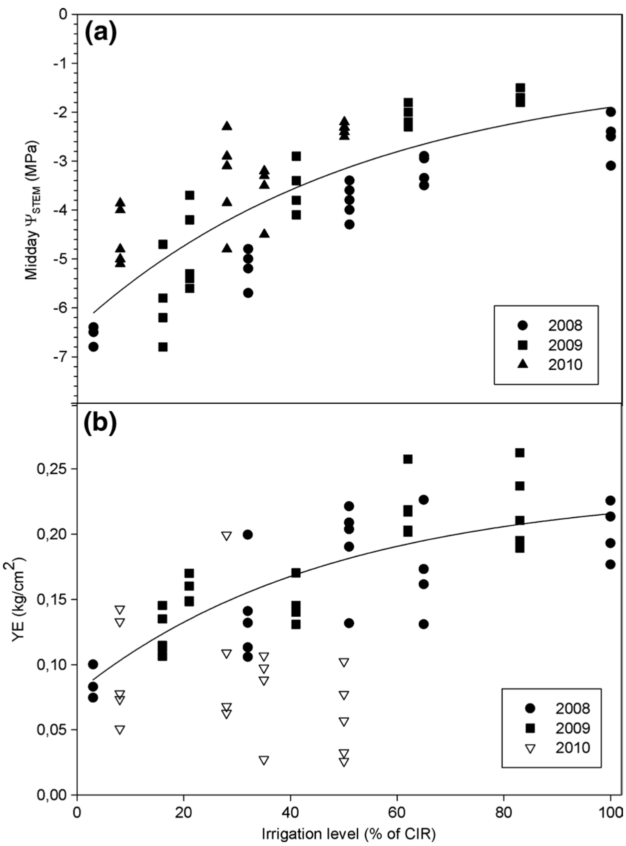

Fig. 3 Relationship between the irrigation levels (% of CIR) and (**a**) midday stem water potential (Ψ_{STEM}, MPa) during the most stressed measurement days of each season (04 September 2008, 01 September 2009 and 23 August 2010) and (**b**) yield efficiency (YE, kg/cm^2 TCSA) in three experimental years. Regression in (**a**) performed on the 2008, 2009 and 2010 data together is: $\Psi_{STEM} = -6.39 + 5.30(1 - \exp(-0.02\text{CIR}))$; $r^2 = 0.65$. Regression in (**b**) performed on the 2008 and 2009 data together $\text{YE} = 0.08 + 0.16(1 - \exp(-0.02\text{CIR}))$; $r^2 = 0.60$. *Empty symbols*, corresponding to the year 2010, were not included in the regression analysis

data showed that yield efficiency increased linearly with increasing midday Ψ_{STEM} (Fig. 4a).

The crop density responded differently to midday Ψ_{STEM} in three seasons (Fig. 4b). In 2008 and 2010, there was no significant relationship between midday Ψ_{STEM} and crop density. In 2009, however, crop density was consistently constant (approximately 100 fruits/cm^2) at midday Ψ_{STEM} lower than −2.5 MPa and increased up to ~200 fruits/cm^2 with increasing midday Ψ_{STEM} above −2.5 MPa.

In 2008 the fruit fresh weight increased linearly from 0.90 g to 1.78 g with increasing midday Ψ_{STEM} (Fig. 4c). In 2009, the fruit fresh weight increased with increasing midday Ψ_{STEM} from 1.32 g to a maximum of 1.77 g at midday Ψ_{STEM} of ~ −2.5 MPa. Further increases in midday Ψ_{STEM} caused a reduction in fruit weight to 1.28 g. In 2010, similar to 2008, the fruit weight increased with increasing midday Ψ_{STEM}. Fruit weight significantly decreased with increasing crop density every year (Fig. 5) with the exception of the trees characterized by a midday Ψ_{STEM} lower than −5 MPa. When Ψ_{STEM} was this low, the fruit fresh weight remained at approximately 1.00 g and was not influenced by the crop density.

A strong, positive and nonlinear relationship was found between oil yield and the number of fruits per tree for all the years of experiment (Fig. 6).

Vegetative and reproductive parameters

The number of inflorescences per shoot and the number of fruitlets per shoot (Table 3) were affected by irrigation for 2009, but not 2010. No statistically significant differences (Student's *t* test, $p \leq 0.05$) were found between the average number of inflorescences per shoot in 2009 (5.5 ± 0.39) and in 2010 (5.7 ± 0.27) (Table 3). However, there were significantly more fruits per inflorescence ($p \leq 0.05$) in the spring 2009 (1.8 ± 0.05) versus spring 2010 (1.3 ± 0.08).

The early (May–June) shoot growth rate (SGR) in 2008 was not monitored because it was before the irrigation treatments were started. The 2008 late season growth rate (from mid-August to mid-October) increased with increasing irrigation level (Fig. 7), ranging from 0.01 in the lowest irrigation treatments to 0.1 cm/day in two highest irrigation treatments. However, in 2009, early SGRs of highest irrigation treatments were 0.15 cm/day, while plants irrigated with less than 50 % of CIR had a significantly higher SGR (0.22–0.30 cm/day). Interestingly, plants with a high SGR (0.23–0.30 cm/day) in 2009 also had a low number of inflorescences per shoot (Fig. 7; Table 3), while plants with lower SGR (0.15 cm/day) had a high number of inflorescences per shoots (~7.5).

In spring of 2010, no differences among treatments were found in either the number of inflorescences per shoot (mean value of 5.7) or the SGR (ranging between 0.1–0.15 cm/day).

Pruning weights (Fig. 8) after the 2008 season increased with 2008 irrigation rates ($r^2 = 0.94$), whereas pruning weights decreased with increasing irrigation rate ($r^2 = 0.98$) after the 2009 season. Winter pruning weight following 2008 season (100–300 kg/ha) was much less than that collected the following 2009 season (2000–3500 kg/ha), irrespective of irrigation rate. Irrigation did not influenced the trunk cross-sectional area (TCSA) that increased from 28.5 cm^2 in 2008 to 34.6 cm^2 in 2009 and 39.6 cm^2 in 2010, while no differences were found among irrigation treatments (Table 2).

Table 2 Effects of the irrigation treatments (actual % of CIR) on the trunk cross-sectional area (TCSA, cm^2), fruit yield, yield efficiency (YE, kg/cm^2 TCSA), number of fruits per tree (fruits/tree, no), fruit oil content (% of fresh weight), polyphenols content (mg/kg oil) and oil yield (t/ha)

Year	CIR (%)	TCSA (cm^2)	Fruit yield (t/ha)	YE (kg/cm^2)	Fruits/tree (no)	Oil (%)	Polyphenols (mg/kg)	Oil yield (t/ha)
2008	3	28.1 (*a*)	4.43(*a*)	0.08 (*a*)	2650 (*a*)	18.8	232.2	0.83 (*ab*)
	32	27.1 (*a*)	7.03 (*ab*)	0.14 (*a*)	3473 (*a*)	20.3	260.9	1.42 (*b*)
	51	30.0 (*a*)	10.72 (*bc*)	0.19 (*b*)	4563 (*a*)	10.8	232.4	1.15 (*ab*)
	65	28.1 (*a*)	9.21 (*abc*)	0.17 (*b*)	2976 (*a*)	8.2	218.8	0.75 (*a*)
	100	29.3 (*a*)	11.64 (*c*)	0.20 (*b*)	4007 (*a*)	13.8	162.6	1.6 (*b*)
Average		28.5 (±1.0)	8.83 (±0.62)	0.16 (±0.01)	3622 (±242)	14.38	221.4	1.18 (±0.09)
2009	16	33.5 (*a*)	7.79 (*a*)	0.12 (*a*)	3136 (*a*)	14.2	175.1	1.1 (*a*)
	21	33.8 (*a*)	10.21 (*ab*)	0.16 (*a*)	3295 (*a*)	16.5	121.2	1.68 (*b*)
	41	36.8 (*a*)	9.83 (*a*)	0.15 (*a*)	3091 (*a*)	17.5	91.5	1.72 (*b*)
	62	32.9 (*a*)	13.72 (*bc*)	0.22 (*b*)	4951 (*b*)	15.5	62.5	2.12 (*b*)
	83	35.8 (*a*)	14.55 (*c*)	0.22 (*b*)	6023 (*b*)	13.0	48.9	1.89 (*b*)
Average		34.6 (±1.2)	11.32 (±0.62)	0.17 (±0.01)	4178 (±279)	15.35	99.8	1.71 (±0.09)
2010	8	39.5 (*a*)	7.18 (*a*)	0.10 (*a*)	2634 (*a*)	20	285	1.44 (*a*)
	28	37.6 (*a*)	6.23 (*a*)	0.09 (*a*)	1916 (*a*)	17	362	1.32 (*a*)
	35	37.1 (*a*)	5.41 (*a*)	0.08 (*a*)	1775 (*a*)	18	327	0.99 (*a*)
	–	–	–	–	–	–	–	–
	50	41.5 (*a*)	4.48 (*a*)	0.06 (*a*)	1385 (*a*)	17	285	0.78 (*a*)
Average		39.6 (±1.8)	5.71 (±0.69)	0.08 (±0.01)	1935 (±251)	18.3	315	1.13 (±0.14)

Significant differences among the treatments are denoted by different bracketed letters in italics within a column (Tukey's tests, $p \leq 0.05$); oil percentage and polyphenol analysis were performed on one mixed sample (see text for explanation); thus, no statistical analysis were performed

Discussion

The seasonal irrigation volumes in this experiment that substantially increased yield relative to lower irrigation treatments were similar to those reported previously for traditional, widely spaced olive orchards (Patumi et al. 1999; Pastor et al. 1999; Tognetti et al. 2006), while higher irrigation levels are generally required for SHD orchards (Fernández et al. 2013; Grattan et al. 2006; Gómez-del-Campo 2013b). In this trial, a restitution of 50–60 % of CIR, corresponding to a Ψ_{STEM} value of about −3 MPa and seasonal irrigation volume of about 130 mm, achieved maximum production and maintained high oil quality. This conserved, in the specific experimental orchard condition and crop load, approximately 1200 m^3/ha of water.

The annual yield variations observed in olive plantations are generally associated with the alternate bearing phenomenon typical of this species (Lavee and Wodner 2004). In this study, the yield increase from 8.8 t/ha in 2008 to 11.3 t/ha in 2009 (Table 2) was probably a result of the increasing young tree volume as the trees were only 4 years old in 2008, as indicated by similar YE in both seasons (Table 2; Fig. 3b). In 2010, however, the yield decreased dramatically as a consequence of a sharp decrease in the number of fruit per tree despite further increases in TCSA (Table 2). This suggests the trees were entering alternate bearing (Lavee and Wodner 2004). Alternatively, the heavy pruning required during the winter of 2009/2010 to avoid shade and unfavorable light regime within the canopy, could also be responsible for the sharp yield drop in 2010 (Tous et al. 2010).

The number of fruits per tree is the main determinant of oil yield (Fig. 6), similar to other reports (Ben-Gal et al. 2011; Gucci et al. 2007; Naor et al. 2013), and irrigation clearly affected the number of fruit per tree (Naor et al. 2013).

In 2008, irrigation began at the end of June, after physiological "June fruitlet drop" was completed (Morettini 1950), and therefore too late to have any effect on the current year's fruit load. This could explain why the crop density (no of fruit/TCSA) was unaffected by tree water status in 2008 (Fig. 4b). The increased crop yield in 2008 was correlated with the positive effect of irrigation and tree water status on fruit fresh weight (Fig. 4c; Gucci et al. 2007; Tognetti et al. 2006). It is worth mentioning that this positive effect of irrigation on fruit weight is due to higher quantity of water accumulated in the fruits of the most irrigated treatments. This higher water content negatively affected oil extraction efficiency in high irrigation treatments (Lavee et al. 2007) and also reduced polyphenol content of the oils.

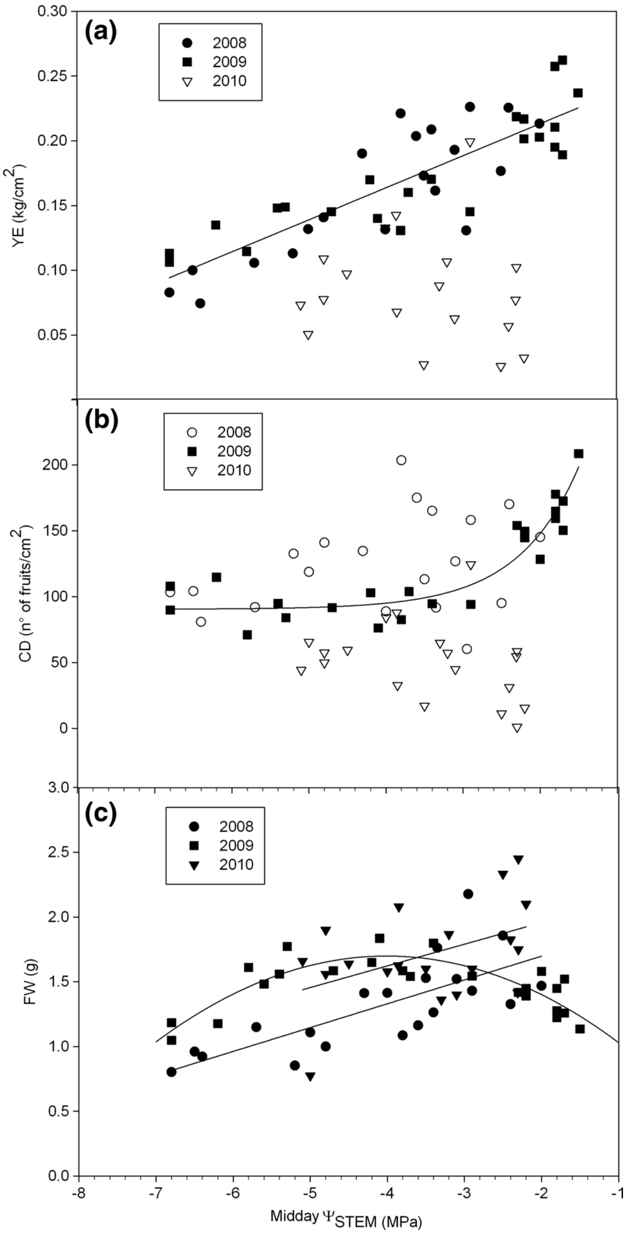

Fig. 4 Relationship between the midday stem water potential (Ψ_{STEM}, MPa) on the most stressed days of measurement (04 September 2008, 01 September 2009 and 23 August 2010 and (**a**) yield efficiency (YE, kg/cm^2 TCSA), (**b**) crop density (CD, no of fruits/cm^2 TCSA) and (**c**) fruit fresh weight (FW, g). The regression lines are: (**a**) 2008 and 2009—$YE = 0.26 + 0.02\Psi_{STEM}$; $r^2 = 0.72$, (**b**) 2009—$CD = 90.5 + 717.1(\exp(1.26\Psi_{STEM}))$; $r^2 = 0.86$, (**c**) 2008—$FW = 2.07 + 0.18\Psi_{STEM}$; $r^2 = 0.55$, 2009—$FW = 0.51 - 0.59\Psi_{STEM} - 0.07x\Psi^2_{STEM}$; $r^2 = 0.71$, 2010—$FW = 2.29 + 0.17\Psi_{STEM}$; $r^2 = 0.20$. *Empty symbols* were not included in the regression analysis

As a consequence, our 2008 fruit oil content, consistent with previous studies (Lavee and Wodner 1991; Pastor et al. 1999; Patumi et al. 1999), was higher in the lower irrigation treatments (Table 2), due to lower water content in low irrigation treatments.

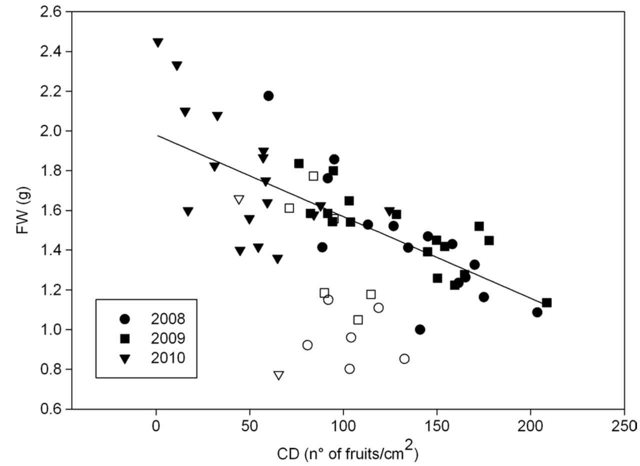

Fig. 5 Relationship between fruit fresh weight (FW, g) and crop density (CD, no of fruits/cm^2 TCSA) in three experimental years. The linear relationships for all the seasons together except for trees that are characterized by $\Psi_{STEM} < -5$ MPa (*empty symbols*) $FW = 1.98 - 0.004CD$; $r^2 = 0.47$)

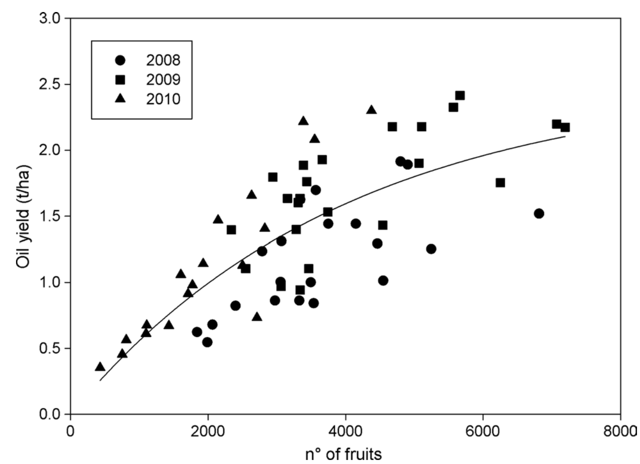

Fig. 6 Relationship between oil yield (t/ha) and the no of fruits per tree during three experimental years. The regression line is: $\text{Oil yield} = 25.2(1 - \exp(-0.0003 \cdot (\text{no. of fruits})))$; $r^2 = 0.57$

Also the concentration of phenolic compounds was negatively affected by the tree water status (Table 2), consistent with other reports (d'Andria et al. 2004; Gómez-Rico et al. 2007; Magliulo et al. 2003; Motilva et al. 2000; Patumi et al. 1999; Servili et al. 2007; Tovar et al. 2002). The large differences found among the 3 years' observations suggested interaction with other parameters, such as climatic conditions. It is known that polyphenols are highly soluble in water, and the pre-harvest precipitation recorded in 2009, higher than in the other 2 years, could have been the cause of the lower concentration of those compounds in the oil produced in 2009. Also the higher crop load observed in 2009 could have determined the

Table 3 Effects of the irrigation treatments (actual % of CIR) of the previous year on the number of inflorescences per shoot at full bloom; number of fruits per inflorescence and number of fruits per shoot at 31 days after full bloom in 2009 and 28 days after full bloom in 2010

CIR 2008	Spring 2009			CIR 2009	Spring 2010		
	Inflorescences per shoot	Fruits per inflorescence	Fruits per shoot		Inflorescences per shoot	Fruits per inflorescence	Fruits per shoot
3	4.6 (*ab*)	1.9 (*a*)	9.2 (*ab*)	16	6.7 (*a*)	1.3 (*a*)	9.0 (*a*)
32	4.6 (*ab*)	1.7 (*a*)	8.6 (*ab*)	21	5.5 (*a*)	1.2 (*a*)	7.0 (*a*)
51	3.4 (*a*)	1.6 (*a*)	6.1 (*a*)	41	6.5 (*a*)	1.0 (*a*)	6.7 (*a*)
65	7.9 (*c*)	1.8 (*a*)	15.7 (*c*)	62	4.9 (*a*)	1.4 (*a*)	7.0 (*a*)
100	7.2 (*bc*)	1.8 (*a*)	14.1 (*bc*)	83	5.2 (*a*)	1.3 (*a*)	7.1 (*a*)
Average	5.5 (±0.39)	1.8 (±0.05)	10.7 (±1.1)	Average	5.7 (±0.27)	1.3 (±0.08)	7.4 (±0.6)

The different bracketed letters in italics indicate significant differences among the irrigation treatments (Tukey's test, $p \leq 0.05$)

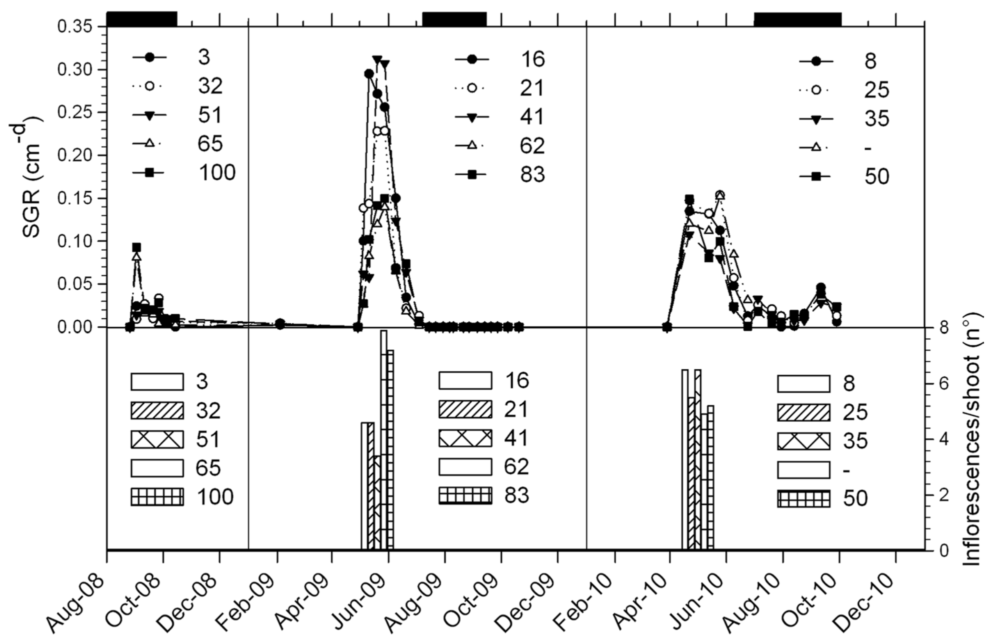

Fig. 7 Effects of the irrigation treatments (% of CIR) on the seasonal pattern of shoot absolute growth rate (SGR, cm^{-d}) during the experimental period (*top*) and average number of inflorescences per shoot (*bottom*). *Black horizontal bars* on the *top* represent the irrigation period

lower polyphenol content of the oils observed in this year (Barone et al. 1994).

The 2008 irrigation regimes increased late tree vegetative growth (Figs. 7, 8; Table 3), required for the following season's bloom density (Dag et al. 2010; Lavee 1996); as a consequence, in 2009 the crop density strongly increased in plants with $\Psi_{STEM} > -2.5$ MPa (Fig. 4b). In 2009, fruit weight increased with increasing Ψ_{STEM} (Fig. 4c) up to −3.5 MPa (similar number of fruit per tree; Fig. 4b). Further increase in Ψ_{STEM} resulted in lower fruit weight that is not expected at higher irrigation levels (Gucci et al. 2009; Inglese et al. 1996; Proietti and Antognozzi 1996). It can be explained by a dramatic increase in the number of fruit per tree (Fig. 4b) that is known to affect fruit weight (Fig. 5; Briccoli Bati et al. 2006; Hartmann 1949, 1952; Lavee and Wodner 2004; Michelakis et al. 1994).

In the same year, the high inflorescence and fruit density (around 7.2 inflorescences and 14 fruits per shoot) in the most irrigated plants directly inhibited early vegetative growth (Fig. 7) and resulted in lower pruning weight (Fig. 8; Sibbett 2000; Dag et al. 2010). Irrigation, in general, positively affects vegetative growth (Gómez-del-Campo et al. 2008; Berenguer et al. 2006) and in our case the response of vegetative growth to crop load override that of irrigation.

Considering that in olive, the current year's fruit is on the vegetative growth of the previous season (Rapoport 2007), our results suggest that the high yields were probably not sustainable for the plants and will exacerbate alternate bearing.

The correlation between midday Ψ_{STEM} and YE (Fig. 3b) was higher than that of CIR with YE (Fig. 4a). It may suggest the use of midday Ψ_{STEM} to adjust irrigation rates.

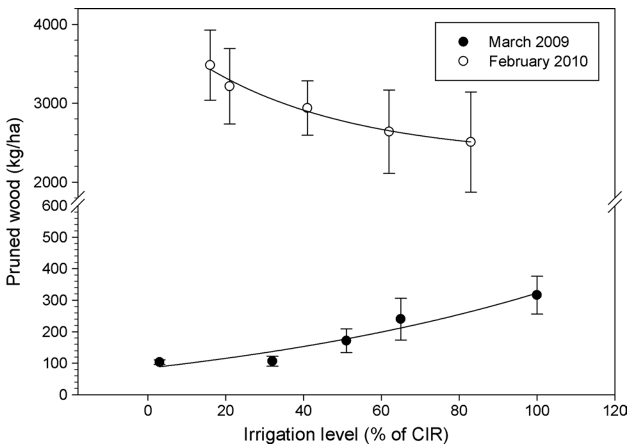

Fig. 8 The winter pruning weight (kg/ha) measured on 02 March 2009 and 04 February 2010 as a function of the irrigation treatment (% of CIR). The regression lines are: 2009—Pruning weight = −56.9 + 141(exp (0.0098CIR)); $r^2 = 0.94$; 2010—Pruning weight = 2315 + 1692(exp (−0.026CIR)); $r^2 = 0.98$

Midday Ψ_{STEM} measures the actual tree water status and may account for variations in water application efficiency and for other sources of variation not considered when using CIR alone (Berman and DeJong 1996; Di Vaio et al. 2012; Naor et al. 1997a, b, 2001; Trentacoste et al. 2011).

The nonlinear positive relationship found between midday Ψ_{STEM} and irrigation treatments (Fig. 3a) has been reported by others in various planting conditions (Ben-Gal et al. 2011; Naor et al. 2013). In particular, in the present work, water applications exceeding 60 % of CIR were less effective in increasing midday Ψ_{STEM} values, demonstrating that irrigation regimes applied above the threshold of about 126 mm per years were excessive, probably percolated into deeper layers and thus reduced irrigation efficiency.

Conclusions

Oil yield increased with increasing irrigation up to a certain level. Further increase in irrigation level increased crop load on the one hand, but decreased vegetative growth and increased the severity of biennial bearing. In addition, the higher irrigation levels decreased oil quality. These results suggest that deficit irrigation management is a viable strategy for SHD olive orchards in order to maintain optimal oil yield and quality. Our results support using midday Ψ_{STEM} for irrigation scheduling in the SHD olive orchards, and the optimal Ψ_{STEM} values for the conditions of the current experiment are between −3.5 and −2.5 MPa.

Acknowledgments This work was funded by the research project PON 2007–2013 PON02_00451_3361785 "Valorizzazione di prodotti tipici della Dieta Mediterranea e loro impiego a fini salutistici e nutraceutici (DiMeSa)." We express our gratitude to Professors JE Preece and L. Ferguson for correcting the English language and for helpful and constructive suggestions. We thank also the editor and reviewers for helpful comments on the manuscript.

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