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RESEARCH ARTICLE

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Effect of complementary irrigation on yield components and alternate bearing of a traditional olive orchard in semi-arid conditions

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Abstract

Traditional olive orchards are usually not irrigated in the Mediterranean basin, but at those latitudes, the yearly rainfall is frequently insufficient to support equilibrated vegetative growth and high fruit and oil production. This three-year field study investigated the effect of complementary irrigation on olive tree vegetative growth, fruit and oil yield during a biennial alternate bearing cycle in a traditional grove under semi-arid conditions. Adult olive trees (*Olea europaea* L. cv. Nabali Baladi) were subjected to complementary irrigation in 2011 and 2012 ('on' and 'off' years, respectively) with 6, 10, 15 or 20 m^3 of water per tree per season, which corresponded to 14.2%, 23.8%, 35.7% and 47.6% of the whole seasonal evapotranspiration (42 m^3 of water per year), respectively. Rain-fed trees were used as control. In 2013, no complementary irrigation was supplied, and any residual effects on the yield components were determined. Results showed that none of the irrigation regimes affected vegetative growth, or olive fruit size (mesocarp and endocarp), as fresh and dry weights. The fruit and oil yield per tree increased compared to the rain-fed conditions only when the threshold of 15 m^3 was exceeded, thus inducing a higher crop load compared to the rain-fed control during the 'off' and even further during the 'on' year. No residual effects were registered in 2013. The study showed that complementary irrigation of at least 35% of the seasonal water requirement can produce remarkable positive effects on fruit yield especially during 'on' bearing years.

Additional key words: crop load; oil yield; yield efficiency; residual effect; olive cv. Nabali Baladi.

Abbreviations used: DW (dry weight); ETc (crop evapotranspiration); FW (fresh weight); MI (maturation index).

Authors' contributions: Coordinated the research project and designed the experiment: EML and FP. Performed the experiment: EML, SA, MM and MQ. Analysed the data and drafted the manuscript: EML and SP. Performed the critical revision of the manuscript: DN.

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Introduction

Olive (*Olea europaea* L.) has important physiological attributes that enable its survival and production in the drought-prone environments of the Mediterranean basin (Connor, 2005). Nowadays, most of the traditional olive groves are usually not irrigated and prolonged drought, high temperatures and year-to-year rainfall variability during the growing season can negatively affect the vegetative growth, the fruit and oil yields (Grattan *et al.*, 2006; Gomez-Rico *et al.,* 2007), thus increasing the natural tendency of the olive trees to alternate bearing (Lavee, 2006) and making unpredictable the economic returns.

In the most drought areas of the Mediterranean, where seasonal rainfall is negligible, water irrigation supplying 75% of the crop evapotranspiration (ETc) had been found to promote up to a four-fold greater fruit production and oil yield compared to rain-fed conditions (Moriana *et al.*, 2003; Grattan *et al.*, 2006), mainly by increasing the number of fruits per tree (Goldhamer *et al.*, 1994; Pastor *et al.*, 1998; Patumi *et al.*, 1999, 2002; D'Andria *et al.*, 2004; Grattan *et al.*, 2006, Gucci *et al.*, 2007). Several studies have also recognized positive effects of an increased water supply to olive trees starting from 30% of the ETc return compared to rain-fed conditions on the fruit size, pulp-to-pit ratio, mesocarp cell size, and oil content at harvest (Lavee *et al.*, 1990; Inglese *et al.*, 1996; Proietti & Antognozzi, 1996; Costagli *et al.*, 2003; Lodolini *et al.*, 2011; Gucci *et al.*, 2007, 2009, 2011).

Recent studies have suggested that it is not necessary to supply the total water requirement (100% of crop evapotranspiration), but it is possible to reduce the amount of water applied during the season without affecting fruit production (Fernandez *et al.*, 2013). No negative effects were registered on fruit and oil yields, nor on yield components compared to the 100% of ETc supply, by reducing the irrigation to a 35-50% of the ETc through regulated deficit or complementary irrigation in different areas characterized by a sub-humid Mediterranean climatic conditions (Alegre *et al.*, 2002; Gucci *et al.*, 2007; Servili *et al.*, 2007; Caruso *et al.*, 2013).

When regulated deficit irrigation in the reason of 25% of the ETc was applied in southern Spain (Mediterranean climate with average 496 mm rainfall during the three-years experimentation), fruit yield was significantly decreased in the 'on' year (high fruit production) and recorded no differences in low-yield year ('off' year) compared to 100% of ETc supply (Iniesta *et al.,* 2009). No significant differences, compared to the full ETc supply, were recorded for the vegetative growth when water irrigation was reduced to 50% of the ETc in harsh weather conditions (130.5 mm of rainfall in the two-year study period) of Kuwait (Bhat *et al.,* 2012). As well, a 70% of the total water requirement applied by regulated deficit irrigation did not affect the vegetative growth and fruit yield of young olive trees in semi-arid conditions (rainfall of 200-300 mm/year) of Morocco (Sikaoui *et al.,* 2014) compared to full ETc return.

In a previous study, Lodolini *et al.* (2014) demonstrated that complementary water irrigation with 35% of the whole seasonal water requirement can produce positive effects on olive fruit production and oil yield in comparison with rain-fed trees in Palestine (semi-arid climatic condition). Despite the numerous studies on olive irrigation, influence on alternate bearing and residual effect after irrigation suspension are rarely approached. In Palestinian conditions, water supply might be aleatory during the years and the potential residual influence of the irrigation on the fruit production in the following year should be considered to control alternate bearing.

The objective of the present study was to investigate the effects of complementary irrigation on vegetative growth, yield and yield components of adult olive trees across two consecutive years, for a biennial alternate-bearing cycle ('on' and 'off' years), as well as on any residual effect in the following year after suspending irrigation. We hypothesized that fruit production and especially oil yield per tree could beneficiate of a complementary irrigation and that the positive effect would be amplified during the 'on' years. We also hypothesized that a better physiological status of the plant during summer, due to complementary irrigation, could lead to a greater flower bud differentiation and consequent fruit set the in the following year, even in the absence of water irrigation supply.

Material and methods

Experimental site and plant material

The trial was carried out in a traditional adult olive grove (*Olea europaea* L. cv Nabali Baladi; Qutub *et al.*, 2010) in the village of Haja (latitude, 32°11'49"N; longitude, 35°07'25"E; altitude 324 m a.s.l.; in the Qalqilya district), in the north-west of Palestine (West Bank) characterized by Terra Rossa soil (Ghanma, 2015).

In the spring of 2011, 25 homogeneous olive trees were selected and the mean (±standard error) trunk cross-sectional area and canopy volume (assuming a cylindrical shape) were measured as 0.16 ±0.01 m^2 and 157.85 ± 10.8 m^3, respectively. The olive trees were spaced 10 m × 10 m (tree density, *ca*. 100 tree/ha).

The treatments were arranged according to a completely randomized design, with five single tree replicates per each complementary water irrigation regime. The different water irrigation treatments were kept well separated, with a one-tree edge to prevent water infiltration that might have confounded the water application regimes. Standard cultivation practices for olive groves in Palestine were followed, with no pruning performed or fertilizers applied during the whole three-year experimentation period. Olive fly was periodically monitored, although no spray applications were needed, as the maximum attack on the fruit through the experimental period was 2.8% in 2011, 0% in 2012 and 1.4% in 2013.

Climatic conditions

Fourteen years of records (1997-2010) from a weather station of the General Department of Meteorology, Ministry of Transport, located in Qalqilya, were used to characterize the climate and estimate evapotranspiration. The climate of the experimental area can be considered as semi-arid Mediterranean, according to the Emberger classification (Nahal, 1981). The pluviometric quotient was 45.4, and the minimum and maximum temperatures of the coldest (January) and warmest (July) months were 8.2°C and 31.7°C respectively. The 14 years annual mean rainfall was 487 mm, mainly distributed in January, February and December; the dry period ranged from April to November, as illustrated in Fig. 1 (climate diagram of the experimental area determined according to Walter & Lieth, 1967).

One data logger (Testo 175-H1, Testo SpA, Milano, Italy) was placed in the olive grove inside the canopy of a tree, to record the air temperature and relative humidity at 60 min. intervals throughout the experimental period. The sensor was shielded from direct sunlight. The precipitation records were obtained from the nearest weather station to the olive grove located at 2.4 kilometers.

The annual precipitation was 485 mm in 2011, 636 mm in 2012 and 623 mm in 2013 (Fig. 2). During the summers of 2011, 2012 and 2013, the average mean temperatures were similar (25.8°C, 26.1°C and 25.5°C, respectively), and the rainfall was negligible (4 mm, 0 mm and 2 mm). In July, the mean maximum temperatures reached 32.1°C in 2011, 33.4°C in 2012 and 32.6°C in 2013.

The comparison of the climatic data over the individual study years with the 14-year mean demonstrated similar average temperatures. In 2012 and 2013 higher yearly precipitations were recorded but no differences on rainfall amount were recorded during the irrigation periods from June to September (Figs. 1 and 2).

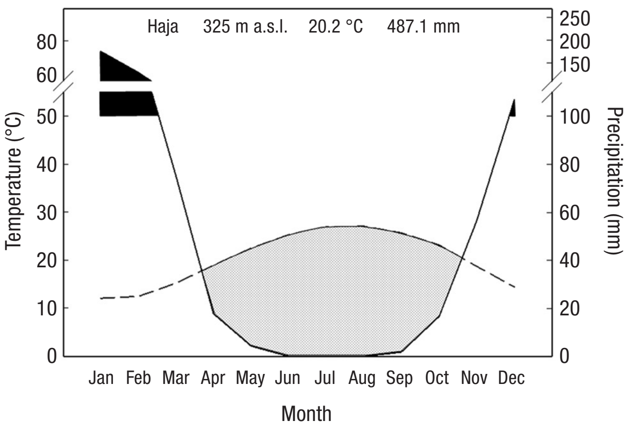

Figure 1. Walter and Lieth's climate diagram for the 1997-2010 period at Haja (Qalqilya district, The State of Palestine). Broken and solid lines show the monthly mean temperatures and precipitation, respectively; dotted area between the lines shows the dry season.

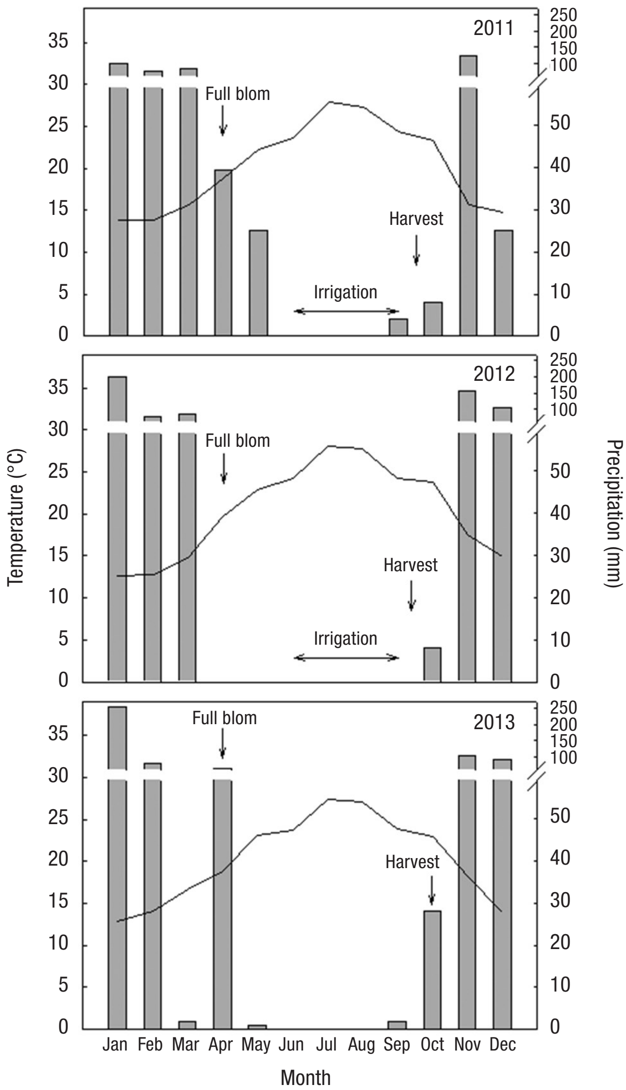

Figure 2. Monthly mean air temperatures (solid line) and precipitation (grey histograms) at the experimental olive grove in 2011, 2012 and 2013.

Irrigation

The total water requirement for olive trees under these Palestinian environmental conditions was estimated by standard methods based on the 14-year weather records for the Qalqilya district. The calculation of the monthly reference evapotranspiration was carried out according to the Hargreaves equation. Crop evapotranspiration was calculated according to the FAO´s method (Doorenbos & Pruitt, 1974) using the monthly crop coefficients, as reported by Orgaz & Pastor (2005) for similar environmental conditions (Jan: 0.82, Feb: 0.83, Mar: 0.59, Apr: 0.50, May: 0.42, Jun: 0.40, Jul: 0.37, Aug: 0.38, Sep: 0.48, Oct: 0.72, Nov: 0.97, Dec: 0.89), and a coefficient of ground cover of 1.0, determined from the mean diameter of the canopy-projected area of each tree at solar noon

(Orgaz & Fereres, 1997). The estimations show that the total water requirement for the olive groves in Palestine (*i.e.* 100% of evapotranspiration) corresponds to *ca*. 42 m^3/tree through the water-deficit season.

In this study, the four complementary water irrigation schedules supplied a total of 6 m^3, 10 m^3, 15 m^3 or 20 m^3/tree of water over the period from mid-June (*ca*. 8 weeks after full bloom) to mid-September (*ca.* 20 weeks after full bloom). A bi-weekly irrigation schedule was used in 2011 and 2012, with no complementary irrigation applied in 2013, to determine any residual effects on the yield components of the olive trees. Several 220 L pierced barrels (from 5 to 16/tree according to the irrigation schedule) were located under the perimeter of the canopy projection on the ground. In each irrigation date, in the late afternoon, the barrels were refilled with water and its release onto the ground was completed within two hours. The supplied water amounts corresponded to 14.2%, 23.8%, 35.7% and 47.6%, respectively, of the total water requirements for olive tree evapotranspiration. Five rain-fed trees were used as the control. The irrigation schedule and the water amount supplied are reported in Table 1.

Vegetative growth and yield components

The canopy volume of each olive tree was calculated from the measurements of the height and the width of its canopy (from the projection on the ground at noon) before the beginning of the experimental period (May 2011), and at harvest for each individual year (assuming a cylindrical shape). Moreover, the summer vegetative growth was calculated for eight one-year-old mixed shoots for each olive tree (= 40 per treatment). These were selected and labelled around the canopy at 1.5 m to 1.8 m from the ground every year of experimentation, with the measurements given as the differences between the lengths at the beginning of the irrigation and at harvest.

Immediately before harvest, 100 fruit were randomly sampled from the whole canopy of each olive tree, for fruit fresh weight measure and for the calculation of the total number of fruit per olive tree estimated by dividing the crop yield by the average fruit weight. The picked fruits were also used to determine the maturation index (MI), according to the standard methodologies: skin and pulp colors, on a scale from 0 to 7, according to Beltran *et al.* (2004). From these same 100 fruits, 20 were selected for the measurement of the weight of its different tissues. Once the pulp had been removed from the fruit, the fresh and dry weight (FW and DW) of the mesocarp + epicarp and the endocarp were measured separately.

The total crop yield per tree was recorded at harvest (on 27 September, 2011, 24 September, 2012, and 14 October, 2013, at 22, 21 and 24 weeks after full bloom, respectively).

The oil content of the fruit mesocarp was determined by extracting the dry material with 40°C to 60°C petroleum ether using a Soxhlet apparatus (Donaire *et al.*, 1977) and combining together the dried pulps of the 20 olive fruits per tree previously sampled for FW and DW. The oil yield at harvest was calculated for individual trees as previously reported by Gucci *et al.* (2007) and Lodolini *et al.* (2014).

Statistical analysis

The influence of the complementary irrigation regimes on yield components was tested using the ANOVA, on single year basis. When the ANOVA indicated significant differences, the means of vegetative growth and yield components parameters were separated by Tukey-Kramer *HSD* test at α level = 0.05. A two-way ANOVA and a paired-samples t-test were conducted to highlight any variability on the influence of water irrigation regimes over time in 2011 and 2012. Statistical analysis was performed using the JMP 11.0 software (SAS Institute, Cary, NC, USA).

Table 1. Water volumes applied to the olive trees for complementary irrigation in 2011 and 2012.

Irrigation timing	**Irrigation treatment (m^3/tree)**			
	6	**10**	**15**	**20**
Mid-June	1.0	1.0	1.6	2.0
End of June	1.0	1.5	2.0	3.0
Mid-July	1.5	1.5	2.2	3.0
End of July	—	1.5	2.4	3.2
Mid-August	1.5	1.5	2.4	3.2
End of August	—	1.5	2.4	3.2
Mid-September	1.0	1.5	2.0	2.4
% Total evapotranspiration (100% = 42 m^3)	14.2	23.8	35.7	47.6

Results

The mean vegetative growth of one-year-old mixed shoots during the irrigation period was 1.56 ±0.17 cm, 1.89 ±0.17 cm and 1.40 ±0.16 cm in 2011, 2012 and 2013, respectively, with no significant differences between water irrigations within each year (Table 2). No differences were recorded also for the canopy volume (not shown).

The fruit yield at harvest, expressed as fresh weight per tree, was significantly higher than the rain-fed control only for the 15 m^3 and 20 m^3 water irrigation regimes in 2011 and 2012 (Table 3). Indeed, the FW of the olive per tree reached more than twice the level of rain-fed control in 2011 (*i.e.*, 20.3 kg *vs* 57.5 kg and 58.3 kg fruit FW per tree for rain-fed *vs* 15 m^3 and 20 m^3 water irrigation, which correspond to 183% and 187% increase, respectively), and was about double when compared to the rain-fed trees in 2012 (*i.e.*, 11.0 kg *vs* 23.5 kg and 25.0 kg fruit FW per tree for rain-fed *vs* 15 m^3 and 20 m^3 water irrigation; 113% and 127% increase, respectively). There were no significant differences between the control (rain-fed) trees and the 6 m^3 and 10 m^3 water irrigation in both 2011 and 2012. In 2013, when no complementary irrigation was applied, there were no significant differences among any of the water irrigation regimes applied the previous year (Table 3).

Similar results were obtained for the number of fruits per tree at harvest (Table 3). In 2011, the 15 m^3 and 20 m^3 water irrigation induced a significant increase to more than twofold the control, being the number of fruit/tree 8,494 *vs* 21,698 and 21,673 respectively (155% increase). In 2012, the fruit number per tree at harvest was more than doubled for the 15 m^3 water irrigation (105% increase) and for the 20 m^3 (107% increase) when compared to rain-fed control. In both 2011 and 2012, no significant differences were seen between the rain-fed trees and the 6 m^3 and 10 m^3 water

Table 2. Seasonal shoot growth of the adult olive trees (cv Nabali Baladi) under the different complementary irrigation regimes. ANOVA and Tukey-Kramer mean separation test ($\alpha = 0.05$). Mean ± standard deviation of n = 40 replicates.

Irrigation (m^3/tree)	Shoot growth (cm)		
	2011 n = 40	2012 n = 40	2013[1] n = 40
Rain-fed	1.39 ± 0.15	1.95 ± 0.16	1.39 ± 0.14
6	1.36 ± 0.18	1.85 ± 0.17	1.36 ± 0.14
10	1.54 ± 0.18	1.78 ± 0.18	1.38 ± 0.18
15	1.65 ± 0.17	1.89 ± 0.16	1.49 ± 0.17
20	1.88 ± 0.17	1.97 ± 0.18	1.39 ± 0.16
	n.s.	n.s.	n.s.

n.s.: no significant differences were found between the water irrigation regimes within each year (p>0.05). [1] No complementary irrigation applied.

Table 3. Yields, yield components and maturation indices (MI) of adult olive trees (cv Nabali Baladi) under the different complementary irrigation regimes in three consecutive years. ANOVA and Tukey-Kramer mean separation test ($\alpha = 0.05$). Mean ± standard deviation of n = 5 replicates.

Year	Irrigation (m^3/tree)	Fruit yield (kg/tree) n = 5	Fruit/tree (n) n = 5	Oil yield (kg/tree) n = 5	Fruit FW (g/fruit) n = 5	MI n = 5
2011	Rain-fed	20.3 ± 1.1^b	8,494 ± 762^b	5.0 ± 0.6^b	2.39 ± 0.2^a	1.0 ± 0.3^a
	6	28.1 ± 9.0^b	11,240 ± 836^b	7.0 ± 1.1^b	2.50 ± 0.3^a	0.8 ± 0.0^{ab}
	10	28.9 ± 6.5^b	11,796 ± 1,767^b	7.0 ± 2.0^b	2.45 ± 0.1^a	0.7 ± 0.0^{ab}
	15	57.5 ± 9.1^a	21,698 ± 3,759^a	12.6 ± 1.7^a	2.65 ± 0.4^a	0.7 ± 0.0^{ab}
	20	58.3 ± 1.8^a	21,673 ± 1,302^a	13.4 ± 1.9^a	2.69 ± 0.2^a	0.6 ± 0.2^b
		<0.0001	<0.0001	<0.0001	n.s	0.027
2012	Rain-fed	11.0 ± 2.8^b	4,867 ± 1,742^b	3.6 ± 1.2^b	2.26 ± 0.7^a	1.7 ± 0.0^a
	6	17.4 ± 2.2^{ab}	7,342 ± 677^{ab}	3.8 ± 0.6^b	2.37 ± 0.1^a	0.9 ± 0.1^b
	10	17.5 ± 2.2^{ab}	7,675 ± 2,358^{ab}	4.1 ± 1.4^b	2.28 ± 0.3^a	0.8 ± 0.0^b
	15	23.5 ± 7.9^a	10,000 ± 2,696^a	5.1 ± 1.5^{ab}	2.35 ± 0.1^a	0.5 ± 0.0^c
	20	25.0 ± 4.3^a	10,081 ± 1,191^a	6.6 ± 1.4^a	2.48 ± 0.3^a	0.5 ± 0.1^c
		0.0006	0.0015	0.0064	n.s	<0.0001
2013[1]	Rain-fed	16.1 ± 2.0^a	7,564 ± 1,316^a	5.0 ± 0.9^a	2.38 ± 0.6^a	0.6 ± 0.0^a
	6	18.0 ± 3.9^a	7,500 ± 782^a	5.1 ± 0.7^a	2.40 ± 0.3^a	0.8 ± 0.1^a
	10	18.3 ± 5.1^a	7,561 ± 1,587^a	5.5 ± 1.1^a	2.42 ± 0.4^a	0.9 ± 0.1^a
	15	18.6 ± 1.4^a	7,560 ± 1,387^a	5.5 ± 0.7^a	2.46 ± 0.3^a	0.6 ± 0.1^a
	20	21.1 ± 5.7^a	7,602 ± 1,281^a	5.2 ± 1.2^a	2.65 ± 0.3^a	0.8 ± 0.2^a
		n.s	n.s	n.s	n.s	n.s

Different letters in a column within each year indicate significant differences (p<0.05). n.s.: no significant differences were found between the water irrigation regimes within each year (p>0.05). [1] No complementary irrigation applied. The irrigation column refers to the irrigation treatment applied during the previous two years.

irrigation. As for fruit yield, in 2013, when no complementary water irrigation was applied, there were no significant differences in the number of fruit per tree depending to the previously assigned water irrigation regimes.

When the oil content in the fruit was expressed as a percentage on the DW, this did not show any direct relationship with the water irrigation regimes across the full three-year experimental period (data not shown). Instead, the oil yield per tree at harvest was positively affected by the higher levels of water irrigation in both 2011 and 2012 compared to the rain-fed control (Table 3). In particular, in 2011 ('on' year), the oil yields for the 15 m^3 and 20 m^3 water irrigation regimes showed increases of 152% and 168% over that of the rain-fed trees, and in 2012 ('off' year), these were 41% and 83%, respectively. Thus, there was more than a doubling of the oil yield per tree in 2011 when rain-fed trees were compared with the 15 m^3 and 20 m^3 water irrigation (*i.e.*, 5.0 kg *vs* 12.6 and 13.4 kg) and less than a doubling in 2012 (*i.e.*, 3.6 kg *vs* 5.1 and 6.6 kg; Table 3). There were no significant differences between the rain-fed trees and the 6 m^3 and 10 m^3 water irrigation in both 'on' and 'off'. Even for the oil yield per tree, there were no significant differences due to a residual effect of the previously assigned water irrigation regimes in 2013, when no complementary irrigation was applied.

No significant differences were found between irrigated and rain-fed trees for the fruit size the mesocarp and endocarp weight and the pulp-to-pit ratio at harvest, both on a FW and DW basis across the three experimental years (data not shown).

The fruit MI at harvest was decreased by increasing water irrigation in both 2011 and 2012 (Table 3). The rain-fed trees showed higher values of fruit MI (1.0 in 2011 and 1.7 in 2012), with a consistently significant lower value between the control and the 20 m^3 water irrigation (p = 0.027 in 2011 and p < 0.0001 in 2012). Rain-fed conditions (control) induced a particularly high MI in 2012 (Fig. 3) compared to 2011 despite a general lack of difference for this parameter between the two years in all other irrigation levels. No differences were recorded in 2013.

Comparing 2011 and 2012, the paired-samples t-test indicated lower values in 2012 for fruit yield (mean

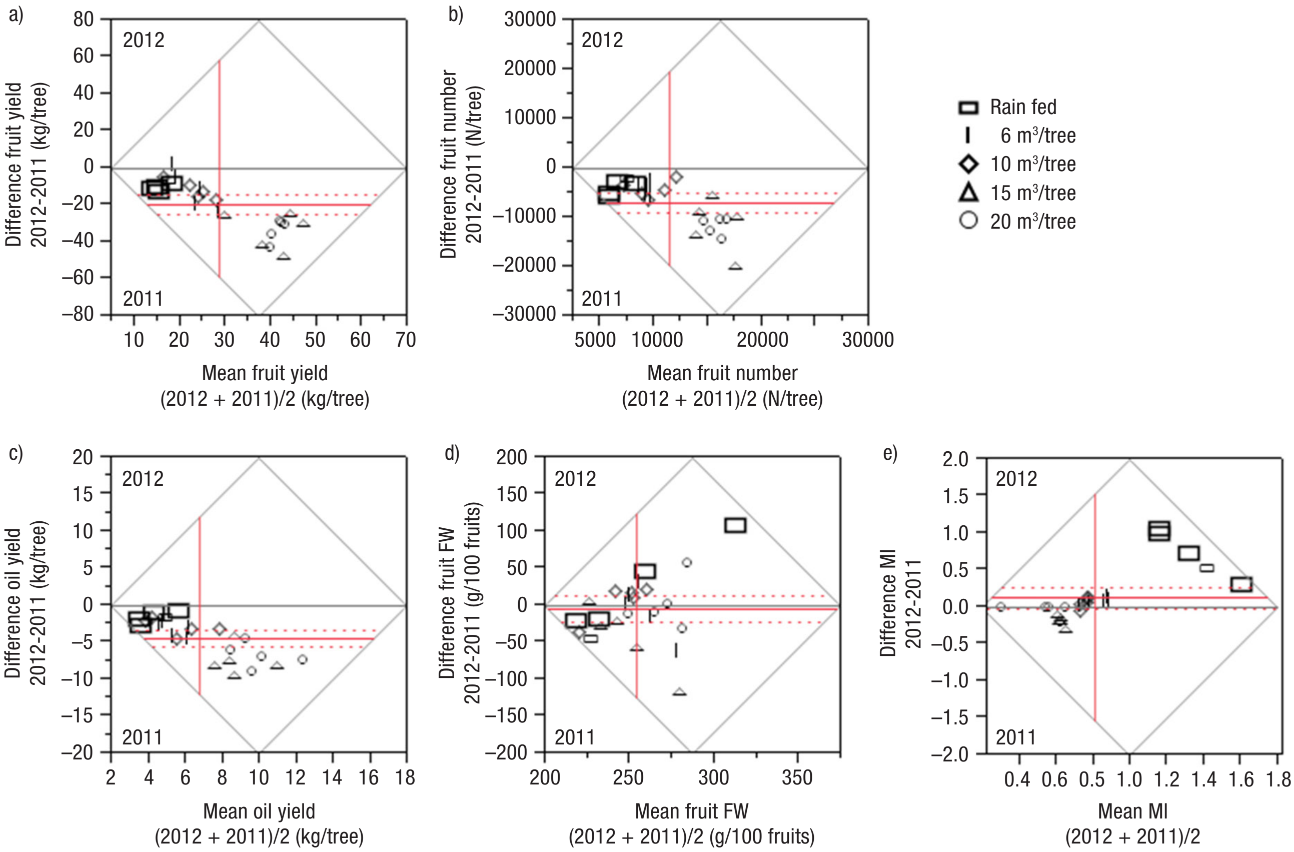

Figure 3. Paired-samples t-test comparing (a) fruit yield (kg/tree), (b) fruit/tree (n), (c) oil yield (kg/tree), (d) fresh weight (FW) of 100 fruits (g/100 fruits), (e) maturation index (MI), in 2011 and 2012 on the 5 trees per treatment. Dotted lines represent the confidence interval (95%) of average difference between 2012 and 2011 values. Symbols below the dotted line indicate higher values recorded in 2011 than in 2012 for each single tree. Vertical line represents the average of mean yearly values calculated as (2012+2011)/2. Symbols on the left of the vertical line indicate values exceeding the total average.

difference 2012-2011 = -19.7, SE = 2.7), fruit number (mean difference 2012-2011 = -6987, SE = 932.8) and oil yield (mean difference 2012-2011 = -4.34, SE = 0.5) with t(24) = -7.3, -7.4 and 8.0, respectively. Thus confirmed the 2011 as an 'on' year and the 2012 as an 'off' year. No difference were recorded for fruit fresh weight (mean difference 2012-2011 = -4.8, SE = 8.9, t(24) = -0.54) and MI (mean difference 2012-2011 = 0.13, SE = 0.07, t(24) = 1.84) among the two years (Fig. 3).

The two-way ANOVA comparing 2011 and 2012 indicated no effect due to the treatment for the fruit fresh weight (p = 0.34) and confirmed no effect due to year (p = 0.58) nor a *treatment*year* interaction (p = 0.25). A significant effect due to irrigation regime was registered for the fruit and oil yield, fruit number/tree, and MI (p<0.0001). Such an effect was not uniform over the years in all cases (*treatment*year* p<0.0001) (Table 4). The paired samples t-test (Fig. 3) provided further information on irrigation effects over the two years. Namely the 15 m^3 and 20 m^3 water treatments increased fruit yield, fruit number and oil yield per tree compared to the other irrigation treatments. These effects were greater in 2011 than in 2012 (2012-2011 differences resulted particularly negative in 15 and 25^3 treatments).

For the biennium 2011-2012, significant increases were seen for the higher water irrigations (15 m^3 and 20 m^3) in terms of the cumulative fruit yield, fruit number and oil yield per tree, compared to the rain-fed trees. The fruit yield, fruit number and oil yield per tree for the rain-fed trees (31.3 kg/tree, 13,361 fruit/tree, 8.6 kg/tree, respectively) were more than doubled by the 15 m^3 and 20 m^3 water irrigation (Table 5).

Discussion

Complementary water irrigation with ≥35% of the total seasonal water requirement (≥15 m^3) showed significant increases in yield parameters of the adult productive olive trees in the semi-arid environmental conditions of Palestine. When compared with the rain-fed trees and those receiving 6 m^3 and 10 m^3 of complementary water irrigation, in both 'on' and 'off' year, the highest tested irrigation levels (*i.e.*, 15 m^3 and 20 m^3) significantly increased fruit yield, fruit number, and oil yield per tree. In contrast, when no complementary irrigation was applied in 2013, no significant differences for yield, and yield components were recorded due to the water irrigation regimes assigned the previous years. Since any effect on blooming and fruit set should be excluded, being water application started in mid-June, we might hypothesize that 15 m^3 and 20 m^3 water irrigation, applied in 2011 and 2012, may have reduced fruit abscission, as reported by Lavee (1990) and Inglese *et al.* (1996) although this cannot be directly confirmed in the present study since fruit drop was not measured. Despite the initial hypothesis, there were no positive effects of summer irrigation on flower differentiation in the following year so that no re-

Table 4. Two-way ANOVA testing the effect of irrigation treatments, years and their cross interaction on yield components, fruit fresh weight (FW) and maturation index (MI).

	Fruit yield (kg/tree)	Fruit/tree (n)	Oil yield (kg/tree)	Fruit FW (g/fruit)	MI
Irrigation	<0.001	<0.001	<0.001	0.34	<0.001
Year	<0.001	<0.001	<0.001	0.58	0.0014
Irrigation * Year	<0.001	<0.001	<0.001	0.25	<0.001

Table 5. Cumulative yields and yield components of the adult olive trees (cv Nabali Baladi) under the different complementary irrigation regimes for the biennium period of 2011 and 2012. ANOVA and Tukey-Kramer mean separation test (α = 0.05). Mean ± standard deviation.

Irrigation (m^3/tree)	Fruit yield (kg/tree) n = 5	Fruit/tree (n) n = 5	Oil yield (kg/tree) n = 5
Rain-fed	31.3 ± 3.6[b]	13,361 ± 2,156[c]	8.6 ± 1.7[b]
6	45.5 ± 4.5[b]	18,582 ± 845[b]	10.8 ± 1.5[b]
10	46.4 ± 4.6[b]	19,471 ± 3,753[b]	11.1 ± 3.3[b]
15	81.0 ± 13.5[a]	31,698 ± 3,662[a]	17.7 ± 2.5[a]
20	83.3 ± 8.7[a]	31,754 ± 792[a]	20.0 ± 2.9[a]
	<0.0001	<0.0001	<0.0001

Different letters indicate significant differences between water irrigation regimes (p<0.05).

sidual effects were recorded after the suspension of the irrigation.

In the present study, the fruit size was not affected by complementary irrigation, thus indicating that water supply up to 35% was not able to increase cell size. The cell size is recognized as the most sensitive parameter to water stress and responsible for lower fruit size in case of water shortage experienced starting from 8 weeks after full bloom (Rapoport *et al.*, 2004) being the two-third of the cell number already defined at this stage (Hammami *et al.*, 2011). A lack of difference on cell size might explain why the oil content in the fruit was also not affected by complementary irrigation despite the fact that irrigation was provided from 8 to 20 weeks after full bloom when mesocarp growth and oil accumulation may be strongly influenced by water availability (Gucci *et al.*, 2009). The lower drop rate and the higher number of fruits per tree might have reduced single fruit oil accumulation in irrigated trees (Gomez del Campo, 2013) thus contributing to zeroing the differences on fruit FW due to irrigation treatment. Nevertheless the increase of fruit number in the highest irrigation levels, contributed to the higher oil yield per tree. In our environmental conditions, the 15 m^3 water irrigation regime appears to be a possible threshold to significantly reduce fruit drop in order to increase fruit and oil yields per tree.

Effects were stronger in the 'on' than in the 'off' year. These results confirm those of Lavee *et al.* (2007), who reported more effects on the yield in the 'on' than in the 'off' years when a 50% ETc water irrigation regime was applied to Muhasan cultivar, in similar climatic conditions. Reported results are substantially consistent with those presented by Moriana *et al.* (2003) in southern Spain where fruit number and yield per tree were increased in 'on' years but a lack of effect was recorded in 'off' years, when 75% of ETc was applied to adult olive trees in comparison to rain-fed ones.

Results of our study are in contrast with Tognetti *et al.* (2006) reporting no significant differences between rain-fed and 33% of ETc irrigated trees regarding the crop yield in both 'off' and 'on' years for Frantoio and Leccino cultivars in southern Italy. This is probably due to a different rainfall distribution in the area (periodical showers during summer) compared to the climatic conditions in this study.

Furthermore, the data from the present study support those reported by D'Andria *et al.* (2009) and Ben-Gal *et al.* (2011), who indicated that significantly higher fruit yield and oil yield per tree were possible when a higher crop load was ensured. In our case, the irrigation (≥15 m^3) affected the crop load and the correlated parameters.

The higher water irrigation levels supplied in the present study did not affect fruit growth during summer, or fruit mesocarp, endocarp and pulp-to-pit ratio at harvest, on both a FW and DW basis, with no significant differences across the water irrigation regimes. Similarly, no significant increases were recorded for the vegetative growth of the mixed shoot during the irrigation period (mid June – mid September), over the whole experimental period (three years) even for the 20 m^3 water irrigation. This suggests that even higher amounts of water will be required to stimulate vegetative growth during summer under these semi-arid environments. The lack of increase in vegetative growth did not support any increase in the fruit number in the following year.

This is consistent with Ben-Gal *et al.* (2011) that analyzed the influence of bearing cycles on the oil production response to irrigation in Israel. They concluded that tree oil yield increases as a function of increased irrigation only in the 'on' (high fruit bearing) seasons, because of the higher vegetative growth during the 'off' seasons that supports a higher number of fruits in the following year.

No residual effects for the yield and yield components were recorded in 2013 when no complementary irrigation was applied.

The data from the present study show that complementary water irrigation carried out every 2 weeks through the summer period to supply at least 35% of the total calculated evapotranspiration needs of the adult olive trees (*i.e.*, of 42 m^3 water) helps to increase the yield of traditional olive orchards. Indeed, as previously indicated (Lodolini *et al.*, 2014), this amount of 15 m^3 water irrigation per tree represents a threshold to obtain significant increases in the fruit and oil yields, compared to the rain-fed condition or to lower water irrigation regimes, but is ineffective to stimulate vegetative growth and effectively reduce alternate bearing in semi-arid conditions.

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