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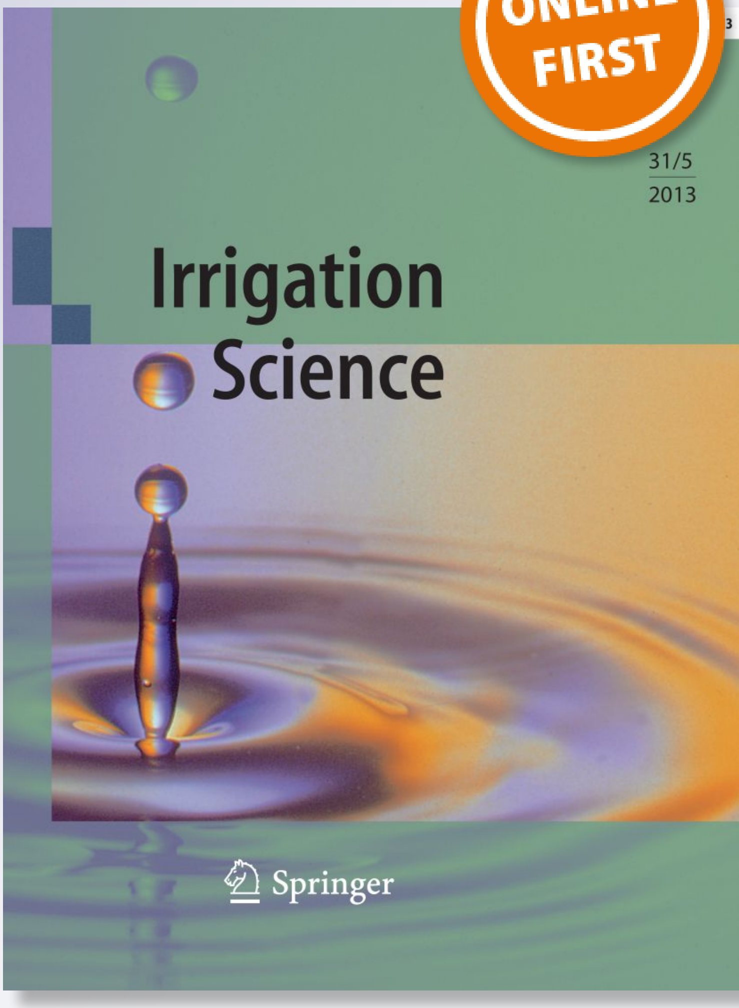

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ORIGINAL PAPER

Effect of regulated deficit irrigation during the vegetative growth period on shoot elongation and oil yield components in olive hedgerows (cv. Arbosana) pruned annually on alternate sides in San Juan, Argentina

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Abstract

In super-intensive hedgerows, vegetative vigor must be controlled to allow access to harvesting machinery, particularly under Argentina conditions in which olive trees display excessive vigor. During shoot growth (spring–early summer), flowering and fruit set also take place and the potential yield (bud number) for the following season is defined. The effect of spring–early summer deficit irrigation was studied as a tool to reduce vegetative growth and its influence on inflorescence development, oil yield, and its components. During three seasons in an olive hedgerow (cv. Arbosana), we evaluated a control irrigated at 70% ETc over the season and two regulated deficit treatments irrigated at 50% (RDI-1) and 30% (RDI-2) ETc during the shoot growth period (from August to January) and then 70% ETc until harvest (May). Hedgerows were mechanically topped and pruned annually on alternate sides. We observed that RDI-1 and RDI-2 reduced hedgerow height and width increment after hedging by 15% and 20%, respectively, compared to control. Inflorescence structures were not affected by water deficit, but the control treatment showed on average 5.8 fruits per fruiting inflorescence, significantly higher than 2.4 fruits per fruiting inflorescence observed in RDI-2. After the third season, RDI-1 and RDI-2 were 174% and 146% more productive than control hedgerows, where the pruned sides showed excessive vigor with lower floral bud induction in the following seasons. Fruit size and oil accumulation were also higher in both RDI-1 and RDI-2 than in control, due to greater fruit exposure to irradiance in most deficit treatments. Compared with control, RDI-1 and RDI-2 allowed water savings of 17% and 35%, respectively, but RDI-1 was more productive and had lower alternate bearing than RDI-2.

Introduction

From the year 2000, Argentina has expanded its olive orchard area trained in hedgerows to obtain earlier and greater fruit yield and to facilitate mechanized harvest. Two types of olive hedgerows have been developed suited to mechanical over-row harvesters. The first are narrow hedgerows planted at super-high density (SHD, 1500–2000 trees/ha) and maintained around 2.5 m height and 1.0–1.5 m width suited to grape harvesters. The second are large hedgerows planted at high density (HD, 250–500 tree/ha) and maintained around 4.5 m height and 4 m width suited to a large "Colossus" harvester (Trentacoste et al. 2015a). At present, many olive hedgerow orchards experience problems due to (1) uncontrolled excessive vigor that leads to hedgerow widths that hinder passage of the harvester, having to resort to manual harvest or (2) hedgerow dimensions are controlled by severe pruning allowing mechanized, but with severe yield penalty (Albarracín et al. 2017). Canopy management is unresolved in both hedgerow types, but in narrow hedgerows, limitations to mechanical harvest occur earlier.

In olive trees, the vegetative growth period occurs mainly in spring–early summer. This period is considered highly sensitive to water deficit, since the actual fruit number is defined (floral quality, fruit set, and fruit fall) in shoots developed during the previous season (Hartmann and Porlingis 1957), as well as the potential number of flowering

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buds for the following season. In olive hedgerows, however, few studies have focused on evaluating water-deficit strategies, such as regulated deficit irrigation (RDI), for vegetative growth control (Hernandez-Santana et al. 2017; Padilla-Díaz et al. 2016; Rosecrance et al. 2015). This can be explained by the fact that winter–spring rainfalls in mediterranean climates limit the early management of plant water status (Iniesta et al. 2009). In contrast, in western Argentina, rainfall is concentrated in summer, and there are opportunities for management of plant water status and vegetative growth (Trentacoste et al. 2015b; Correa-Tedesco et al. 2010). Regulated deficit irrigation (RDI) consists in applying an amount of water below full irrigation needs (i.e., deficit irrigation) and at variable level in a specific development stage over the growing season (Chalmers et al. 1981). In olive, RDI has been evaluated mostly focusing on water savings without a negative impact on yield (Iniesta et al. 2009). It has been observed that vegetative rather than reproductive growth in olive trees is more sensitive to water deficit. Hernandez-Santana et al. (2017) studied different regulated deficit irrigation levels in SHD olive hedgerows (1667 trees/ha), where 60%, 45%, and 30% of the full irrigation needs were applied in short periods during vegetative and fruit growth. The authors found that RDI strategies reduced leaf area significantly with less than proportional reduction in oil yield. In this study, RDI was applied after considerable shoot elongation, inflorescence development, and flowering occurred. Similarly, Rosecrance et al. (2015) in SHD olive hedgerows cv. Arbequina observed higher oil yield and lower vegetative growth under moderate rather than mild water-deficit regimes applied from 70 days after full bloom until harvest. Palese et al. (2010) in HD olive orchards (556 trees/ha) compared irrigated vs non-irrigated treatments and found that water deficit in spring reduced shoot elongation in both dry and wet years, while fruit yield was only reduced in a dry year.

The period prior to bloom is critical for floral formation, and thus, fruit yield determination (Gómez-del-Campo and Rapoport 2008). Olive tree exposure to water deficit 10 weeks before full bloom strongly affects inflorescence structure and flower quality (Rapoport et al. 2012). In central Argentina, Pierantozzi et al. (2014) evaluated four irrigation levels (100%, 75%, 50%, and 25% ETc) during the 4 months prior to bloom in a traditional olive orchard (100 trees/ha). The authors observed that higher water deficit (25–50% ETc) reduced vegetative growth, inflorescence characteristics, fruit set, and fruit number, and led to markedly lower olive yield compared to both 70% and 100% ETc treatments. In relation with the studied variability of crop response to water deficit depending on intensity, period, duration, crop characteristics, and environmental conditions, RDI is more widely used to save water after fruit set than the vegetative control strategy (Hernandez-Santana et al. 2017).

In narrow hedgerows, controlling vegetative growth could compensate a possible yield reduction with advantages to mechanical over-row harvest such as lower costs, shorter harvest time, and reduced alternate bearing (Connor et al. 2014). The lower vegetative growth could lead to higher transmission of irradiance within hedgerows with consequent higher floral bud induction, greater flower quality, fruit set (Trentacoste et al. 2017; Rosecrance et al. 2015), fruit size, and fruit oil content, which can partially compensate lower fruit number (Connor et al. 2016). In addition, olive hedgerows with lower vegetative growth would require lower pruning intensity leading to higher fruit yield (Albarracín et al. 2017). The present irrigation study was conducted on hedgerows pruned laterally in alternate years. In a recent study on well-irrigated hedgerows, we observed that lateral hedging retained fruit load on the unpruned side that controlled vegetative growth on the pruned side and improved irradiance transmission within hedgerows (Trentacoste et al. 2018a). However, we focused on the distribution of fruit production within different canopy positions, although vegetative response was not studied. Therefore, the main hypothesis of this work is that an optimum water deficit during the shoot growth period would lead to control of hedgerow dimensions with a reduced effect on oil yield penalty.

The aim of this work was to study the effect of two regulated deficit irrigation strategies during the shoot elongation period on canopy dimension, inflorescence development, oil yield, and its components in hedgerows managed with annual lateral pruning of alternate sides. To better understand the overall deficit irrigation response, shoot development and growth, oil yield, and fruit characteristics were studied from both pruned and unpruned hedgerow sides.

Materials and methods

Site and orchard

The experiment was carried out during seasons 2015–2016, 2016–2017, and 2017–2018 in a commercial olive (cv. Arbosana) orchard at Cañada Honda Valley (31°58′S, 68°32′W, 614 m.a.s.l.), San Juan, Argentina. The hedgerows were established in 2011 with rows oriented N–S and trees spaced 1.75 m × 3.5 m (1632 trees/ha). The climate of the region is arid with an annual rainfall of 195 mm concentrated in the summer months and an average annual temperature of 18.5 °C. The soil is sandy loam with high gravel content below 0.8 m of depth. Daily meteorological data, recorded at an automated weather station located near the experimental site, included maximum and minimum temperatures, relative humidity, and rainfall. Fertilizer was applied with irrigation water to supply 58.2 kg/ha of N, 10.4 kg/ha of P, 22.0 kg/ha of K, and 8.7 kg/ha of Mg during the first two growing seasons.

Hedgerow pruning—comprising topping and single-side hedging—was applied by machine with four rotating disks assembled on two rotating booms in winter. Topping was set at 3.0 m height and hedging at 0.4 m from the trunk in single passes on July 5, 2015 for the west side, June 25, 2016 for the east side, and July 17, 2017 for the west side.

Irrigation treatments and experimental design

Three irrigation regimes were established: a control and two regulated deficit irrigation (RDI) treatments. Control irrigation, corrected for effective rainfall, was applied to restore 70% of the crop evapotranspiration (ETc) over the whole growing season (from bud break to post-harvest). This treatment was selected as control based on the previous studies where water irrigation above 70% ETc increased vegetative growth without a negative impact on reproductive growth in SHD olive orchards (Grattan et al. 2006; Marra et al. 2016).

Crop evapotranspiration was calculated as

$$\mathrm{ETc} = \mathrm{ETo} \times K_c \times K_r, \quad (1)$$

where ETo is reference evapotranspiration (calculated with Penman–Monteith modified by FAO) (Allen et al. 1998), K_c is a seasonally constant crop coefficient = 0.70 estimated for olive trees by Girona et al. (2002) and Correa-Tedesco et al. (2010), and K_r is an empirical coefficient to account for changing crop cover. It was calculated as 2 × crop cover%/100 with a limit of $K_r = 1$ for cover fraction > 50% (Fereres et al. 1982) estimated at the beginning (September) and mid-growth season (January). We used on average $K_r = 0.52$, 0.53, and 0.60 in 2015–2016, 2016–2017, and 2017–2018, respectively. Control trees were irrigated using 2.0 L/h emitters spaced at 0.8 m intervals along a single drip line per hedgerow. In irrigation scheduling, effective rainfall was considered when daily rainfall was ≥ 12 mm, and then, effective rainfall was estimated daily as daily rainfall—12 mm × 0.80 (Puertas 2009).

Two periods were identified: Period I that covered from bud break to the end of shoot elongation (i.e., when shoot growth rate was maintained around zero during two contiguous measurement dates, see below), and Period II that covered from the end of shoot growth until harvest. RDI treatments were irrigated 50% ETc (RDI-1) and 30% ETc (RDI-2) during Period I (i.e., September 1, 2015–January 29, 2016; August 17, 2016–January 2017; and August 8, 2017–January 23, 2018). Next, in both treatments, irrigation continued at 70% ETc just as the control treatment during Period II. During Period I, RDI-1 and RDI-2 trees were irrigated with 2.0 L/h emitters spaced at 1.12 m and 1.87 m, respectively. During Period II in both RDI treatments, drip lines were replaced by others with 2.0 L/h emitters spaced at 0.8 m. In all treatments, irrigation was applied daily for the same amount of time.

Within a commercial olive orchard, a homogeneous plot of six adjacent rows was selected with 50 trees per row. Trunk perimeter and crown volume of all trees (300 trees) were measured. Out of these, nine experimental plots were chosen which consisted of 5 rows × 4 trees with two central trees from the central row used for data collection. Three irrigation treatments were arranged in a completely randomized design with three replicates.

Measurements

Stem water potential, stomatal conductance, and soil water humidity

Midday stem water potential (SWP) was measured in both trees per replicate every 3 weeks (2015–2016) and every 2 weeks (2016–2017 and 2017–2018) on sunny days between 11:30 h and 12:30 h solar time using a Scholander-type pressure chamber (BioControl, Buenos Aires, Argentina). Shoots of the current years with two or three pairs of fully expanded leaves were enclosed in a small plastic bag covered with aluminium foil at least 90 min before measurements.

Stomatal conductance (g_s) was measured the same days as SWP measurements. Measurements of abaxial stomatal conductance were taken from two fully expanded leaves on the east side in both trees per replicate during mid-morning (10:00–11:30 h) using a steady-state porometer (Decagon device SC-1, USA).

Soil water content (SWC) was determined gravimetrically coincidentally with SWP and g_s measurements. Soil samples (200 g) were taken from 0–0.3, 0.3–0.6, and 0.6–0.9 m of depth in two points: near an emitter and in the middle of two contiguous emitters. Soil samples were weighed and dried at 105 °C to constant weight to estimate soil water content as 100 × (soil-wet wt − soil-dry wt)/soil-dry wt. As the distance between emitters changed among treatments during Period I, we calculated SWC-weighted average for each plot, considering that the weighting factors were 0.75 and 0.25 for the control treatment, 0.47 and 0.53 for RDI-1, and 0.32 and 0.68 for RDI-2 for the SWC measured near and between emitters, respectively. SWC measurements were conducted on one replicate to avoid massive soil disturbance, and consequently, data were analyzed graphically, but not statistically.

Hedgerow vegetative structure

Hedgerow structure was described on both trees per replicate immediately after pruning and before harvest. To do this, the height of top and bottom foliage was measured in three positions per tree: near the trunk and at 0.87 m on each side. Hedgerow width was measured at 1.0 and 1.6 m height at three positions in the same trees. Trunk circumference was measured at 0.3 m from the ground together with canopy dimensions.

Shoot growth and reproductive components

Shoot growth and yield development were recorded on one tree per replicate. After mechanical pruning in winter 2015, 2016, and 2017, five shoots were selected and tagged on each side (pruned and unpruned). Shoot length was measured every 3 weeks in 2015–2016 and every 2 weeks in 2016–2017 and 2017–2018, from the beginning of August to mid-May. The daily average shoot growth rate (SGR) between two successive measurements was calculated as

$$\mathrm{SGR} = \frac{L_2 - L_1}{t_2 - t_1},$$

where L_1 and L_2 is shoot length in cm at times t_1 and t_2.

On the same shoots used to monitor vegetative growth, the initial number of buds was counted in August, inflorescences per shoot were counted in mid-October (buds initiated), the number of fruits per shoot, and inflorescences that set fruit on at least one flower (fertile inflorescence) were counted in November. The number of buds was counted again in May to calculate total buds developed on a 1-year-old stem, and internode length was estimated as number of buds/shoot length.

Inflorescence and flower characteristics

At flowering (October 15, 2015; October 6, 2016; and October 22, 2017), thirty inflorescences containing a mixture of open and closed flowers per replicate were collected from both sides of the border trees. Inflorescence length, number of flowers, and perfect flowers per inflorescence were counted.

Oil yield and its components

Olives were harvested separately from each side, combining fruits from two contiguous trees per replicate on May 17, 2016; May 20, 2017; and May 3, 2018. Fruit from each side was weighed immediately at harvest. From a sample of 1 kg, the maturity index was determined by classifying 100 fruits on a scale from 0 to 7 according to skin and pulp color. The total number of fruits on each side was estimated from the weight of 100 fruits and the total harvest weight. Later, 50 fruits were used to determine fruit oil concentration, and another 50 were used to determine pulp/pit ratio in the laboratory. A subsample of 100 fruits was weighed and dried at 60 °C to constant weight to estimate fruit dry weight and water content as 100 × (fresh wt − dry wt)/fresh wt. Oil concentration was measured in duplicate using the method of Avidan et al. (1999) and was estimated as the quotient, in percentage, of oil weight and pulp weight on a fresh (OCFB) and dry (OCDP) basis. Oil yield was calculated as the product of fruit yield and oil concentration on a fresh basis. Water productivity (WP) was calculated as the ratio between oil yield per hectare and total water applied (irrigation + effective rainfall) in mm.

Average fruit weight, pulp/pit ratio, fruit oil concentration, fruit water content, and maturity index per whole tree were calculated as weighted averages by fruit number.

Statistical analysis

ANOVA was used to test the effect of treatments, side, seasons, and treatment by side, and treatment by season interactions on response variables. Means were separated using the LSD test for a level of significance of $\alpha = 0.05$.

Results

Seasonal conditions

Weather conditions are shown in Fig. 1. Rainfall was much higher than the long-term average (156 mm) in 2015–2016 (259 mm) and close to average in 2016–2017 (158 mm) and in 2017–2018 (132 mm). As usual in San Juan, rainfall concentrated between December and May and was only a small fraction of reference evapotranspiration (Table 1). Monthly mean temperatures from August to May in 2015–2016 (19.4 °C) were lower than in 2016–2017 (20.7 °C) and in 2017–2018 (20.9 °C). Between July 1 and August 31, 2017, there were 19 frost events with minimum temperatures − 6 °C, which likely accounts for reduced oil yield in 2017–2018 (Table 4).

Water applied

Seasonal water application calculated in Periods I and II is reported in Table 1. Irrigation plus effective rainfall in control trees replaced 77%, 79%, and 80% ETc during the whole growing season, relatively higher than the planned 70% ETc. Period I had a similar duration in the three seasons (from mid-August to mid-January) and covered a longer and higher atmospheric demand period than recovery Period II (from mid-January to mid-May). Across seasons, water savings for RDI-1 and RDI-2 treatments compared to control were 17% and 35%, respectively.

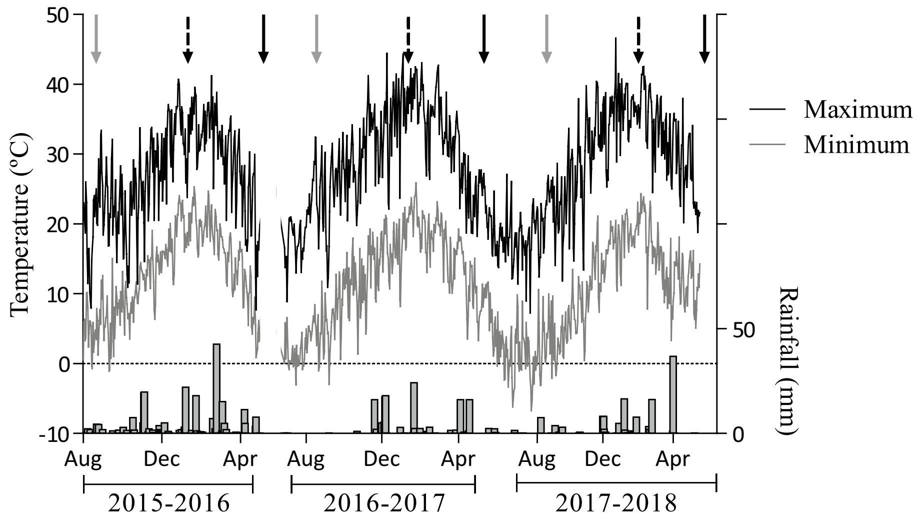


Fig. 1 Daily maximum and minimum air temperature and rainfall during 2015–2016, 2016–2017, and 2017–2018 growing seasons. Arrows indicate the day of key phenostages: budburst (gray), end of shoot elongation (black dotted), and harvest (black)

Table 1 Reference evapotranspiration (ETo), crop evapotranspiration (ETc), effective rainfall (ER), and applied water (AW) accumulated from early August to late-May, and both periods separately, during (Period I) and after (Period II) of vegetative growth in olive hedgerows (cv. 'Arbosana') irrigated with control and two regulated deficit irrigation (RDI) treatments during three growing seasons in San Juan, Argentina

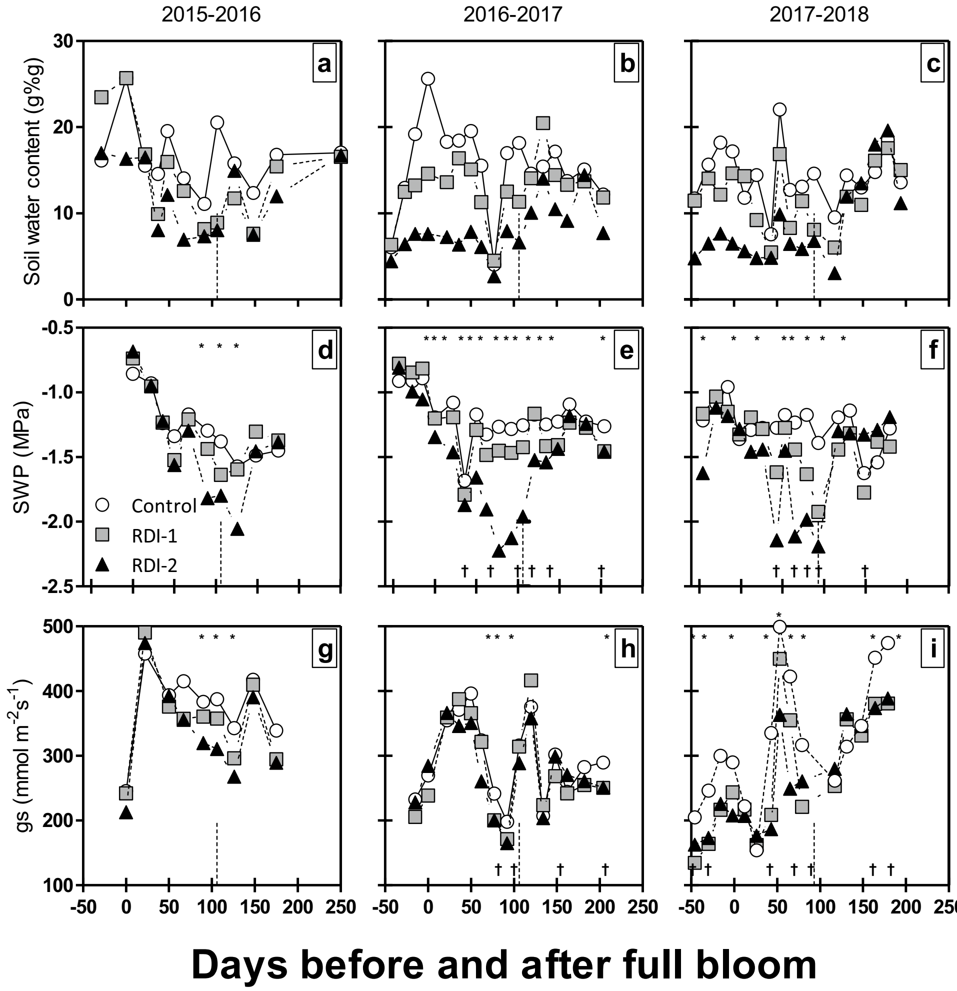
Season	Treatments	ETo (mm)	ETc (mm)	ER (mm)	Applied water (mm)		
					Period I	Period II	Total AW
2015–2016	Control	1255	456.8	101.3	148	104	252
	RDI-1				106		210
	RDI-2				64		168
2016–2017	Control	1500	556.5	67.0	233	138	371
	RDI-1				167		305
	RDI-2				100		238
2017–2018	Control	1372	576.2	43.0	260	156	416
	RDI-1				187		343
	RDI-2				117		273

Soil water content, stem water potential, and stomatal conductance

The SWC pattern varied among seasons and treatments (Fig. 2a–c). In 2015–2016, the experimental plot was irrigated during winter before beginning the experiment, and SWC was high in all treatments ranging from 17 to 22 g % g. After this, SWC decreased until mid-November and remained stable until harvest. In this first season, initial high SWC and heavy summer–autumn rains led to slight differences among treatments. During Period I, SWC averaged 17.1, 15.2, and 11.5 g % g in control, RDI-1 and RDI-2, respectively. During Period II, average SWC was 16.4, 12.1, and 11.8 g % g in control, RDI-1, and RDI-2, respectively. In the last two seasons, irrigation was suspended between harvest and August, thus SWC started low at the beginning of the season, increased sharply with irrigation, and remained stable until harvest. In these last two seasons, SWC varied markedly among treatments and periods. On average, SWC during Period I for 2016–2017 and 2017–2018 was 14.5, 12.2, and 8.3 g % g in control, RDI-1, and RDI-2, respectively. During Period II, average SWC was 14.5, 14.0, and 12.5 g % g in control, RDI-1, and RDI-2, respectively.

Stem water potential (SWP) was highly responsive to irrigation regime (Fig. 2d–f), more markedly in 2016–2017 and 2017–2018 than in 2015–2016. SWP in control trees in 2015–2016 and 2016–2017 dropped sharply from early August to early November, and then remained almost constant until harvest. In 2017–2018, SWP decreased at the beginning of the experiment, but increased sharply from the start of irrigation; after that, it remained almost constant. Across seasons, average SWP was − 1.20 MPa and − 1.35 MPa during Periods I and II, respectively. Under RDI-1, SWP showed a similar pattern to that of control trees, but significantly lower from late Period I to early Period II in the last two growing seasons. Across seasons, average SWP was − 1.27 MPa and − 1.45 MPa during Periods I and II, respectively. Under RDI-2, SWP declined sharply at the beginning of the season—reaching minimum values around − 2.3 MPa at the end of Period I—and tended to recover to the level of control trees during Period II. SWP under RDI-2 was

Fig. 2 Dynamics of midday stem water potential (SWP), stomatal conductance (g_s) and soil water content at a depth of 0–90 cm in response to three irrigation regimes (control, open symbol, RDI-1 gray square, and RDI-2 black triangle) during three growing seasons in olive hedgerows in San Juan. Vertical bars indicate the end of Period I (from bud break to end of shoot elongation) and the beginning of Period II (from end shoot elongation to harvest). Asterisk indicates significant differences between control and RDI-1 and dagger symbol indicates the difference between control and RDI-2 at $P < 0.05$



significantly lower than control during most measurements of Period I and early Period II. Across seasons, average SWP was − 1.52 MPa and − 1.53 MPa during Periods I and II, respectively.

Stomatal conductance (g_s) was also responsive to irrigation regimes (Fig. 2g–i), more evidently in the last two seasons. Stomatal conductance showed a similar pattern among treatments and seasons. During Period I, g_s increased from early August to mid-November and decreased until mid-January, except in 2017–2018 when g_s increased sharply in response to rain (Fig. 2h). During Period II, g_s remained low with occasional increases in response to autumn rains in April 2018. Across seasons, control trees showed an average g_s of 323 and 342 mmol m^2/s during Periods I and II, respectively. Under RDI-1, average g_s was 294 and 320 mmol m^2/s, occasionally lower than control in the last two drier seasons. Under RDI-2, average g_s was 280 and 313 mmol m^2/s during Periods I and II, respectively. This is significantly lower than in control from late Period I to early Period II.

Relative shoot growth and hedgerow structure

Shoot growth rate (SGR) differed significantly among hedgerow sides and irrigation regimes in 2016–2017 and 2017–2018, but they did not differ in 2015–2016 (Fig. 3). In the first season (2015–2016), SGR on the pruned side (Fig. 3a) increased sharply from the beginning of the experiment (20 days before full bloom, DBFB) to 36 days after full bloom (DAFB); after that SGR decreased progressively until 106 DAFB, remaining low and stable ~ 0 cm/day until harvest. Maximum SGR was 0.42, 0.58, and 0.37 cm/day for control, RDI-1, and RDI-2, respectively, with no significant differences over the whole season. On the unpruned side (Fig. 3d), SGR showed a similar pattern and maximum values (0.52, 0.34, and 0.49 cm/day in control, RDI-1 and RDI-2, respectively) as those in shoots on the pruned side.

In 2016–2017, SGR on the pruned side (Fig. 3b) increased progressively from 27 DBFB to 36 DAFB and decreased until 106 DAFB. In this season, SGR showed a slight increase in SGR between 134 and 148 DAFB. Maximum SGR was significantly reduced in RDI-2 (0.19 cm/day)

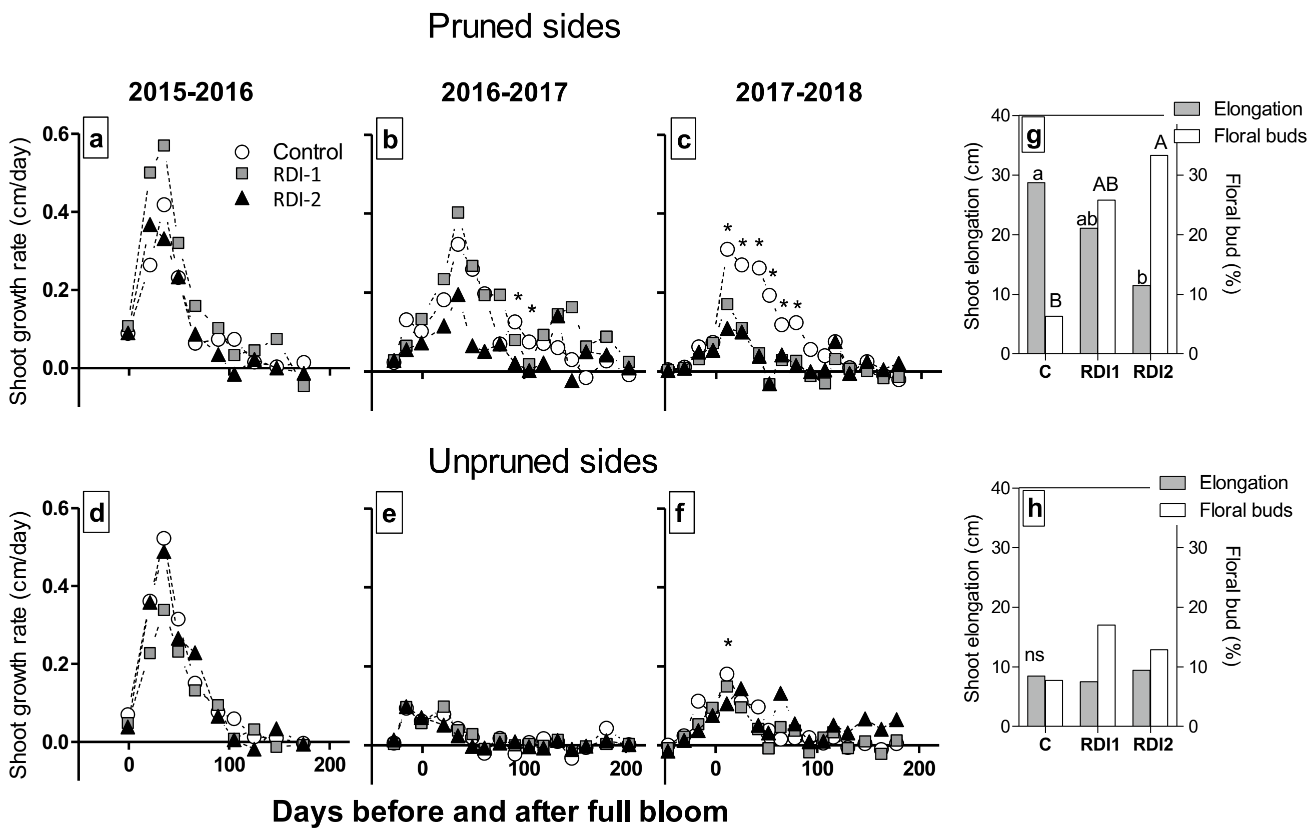


Fig. 3 Dynamics of shoot growth rate on pruned (upper panels) and unpruned (bottom panels) hedgerow pruned laterally in alternate years in response to three irrigation levels (control: open symbols, RDI-1: gray square, and RDI-2: black triangle) during three growing seasons. Asterisks indicate significant differences between control and RDI-2 at $P<0.05$. Right panels show average total shoot elongation from 2015 to 2018 and the percentage of floral bud measured in spring 2016, 2017, and 2018 on pruned (**g**) and unpruned (**h**) sides. Different letters for shoot length (lower case) and for floral buds (upper case) indicate significant differences among treatments at $P<0.05$. *ns* non-significant difference

compared to RDI-1 (0.40 cm/day) and control (0.32 cm/day). In shoots on the unpruned side (Fig. 3e), maximum SGR occurred 15 DBFB and growth stopped earlier than on the pruned side (50 DAFB, i.e., SGR ~ 0 cm/day). On the unpruned side, SGR was not significantly affected by irrigation treatments (0.17, 0.18, and 0.14 cm/day in control, RDI-1, and RDI-2, respectively) and was lower than on the pruned side.

In the last season (2017–2018), on the pruned side (Fig. 3c), maximum SGR occurred 14 DAFB and was significantly higher in control (0.31 cm/day) than in RDI-1 (0.15 cm/day) and RDI-2 (0.11 cm/day). Shoots stopped growth earlier in RDI-1 and RDI-2 (70 DAFB) than in control (100 DAFB). On the unpruned side (Fig. 3f), SGR was maximum at 14 DAFB and growth stopped around 70 DAFB, similarly among treatments. Maximum SGR was significantly higher in control and RDI-1 (0.18 and 0.17 cm/day, respectively) than in RDI-2 (0.11 cm/day).

Hedgerow dimensions after lateral pruning were similar regardless of irrigation treatment, with the exception of hedgerow height in the last pruning (Table 2). Hedgerow width ranged from 0.96 to 1.22 m, and canopy height ranged from 1.85 to 2.39 m. All dimensions matched the recommendation for passage of an over-row harvester. In the last winter pruning, significantly higher hedgerow height in RDC-1 and control than in RDC-2 was mainly due to the height between contiguous trees (i.e., more continuous canopy walls). Hedgerow dimensions in 2016 were not affected by irrigation regimes, but in 2017 and 2018, control hedgerows (width = 1.70 × height = 3.30 m) were significantly taller and wider than RDI-1 and RDI-2 (average 1.20 m × 2.70 m).

The increase in hedgerow dimension from pruning to harvest was highly responsive to irrigation regimes (Table 2) in 2016–2017 and 2017–2018, but this was not the case in 2015–2016. During 2016–2017 and 2017–2018, the increase in canopy width and height was reduced from 0.57 m in width × 1.13 m in height in control to 0.29 m × 0.92 m and 0.11 m × 0.73 m in RDI-1 and RDI-2, respectively. In the last two seasons,

Table 2 Hedgerow dimensions after pruning and at harvest, seasonal increment of hedgerow dimensions, and trunk cross sectional area (TCSA) as affected by three water regimes: control and two regulated deficit irrigation (RDI-1 and RDI-2) treatments

Seasons	Treatments	Canopy size after pruning		Canopy size at harvest		Increment of canopy size from pruning to harvest		
		Width (m)	Height (m)	Width (m)	Height (m)	Width (m)	Height (m)	TCSA (cm^2)
2015–2016	Control	1.22	2.08	1.92	2.50	0.72	0.42	22.59
	RDI-1	1.13	2.15	1.66	2.29	0.54	0.14	20.31
	RDI-2	1.21	2.10	1.70	2.22	0.50	0.12	18.33
2016–2017	Control	1.05	1.91	1.80 a	3.00 a	0.76 a	1.07 a	20.14 a
	RDI-1	1.02	1.83	1.46 b	2.72 b	0.44 ab	0.89 ab	11.32 b
	RDI-2	1.08	1.79	1.18 b	2.56 b	0.10 b	0.77 b	9.64 b
2017–2018	Control	1.11	2.39 a	1.50 a	3.57 a	0.38 a	1.18 a	18.41 a
	RDI-1	1.05	2.18 a	1.19 b	2.87 b	0.14 ab	0.69 b	13.66 ab
	RDI-2	0.96	1.85 b	1.07 b	2.78 b	0.11 b	0.93 ab	9.29 b

Values with the same letter are not significantly different within each year by LSD test at $P \leq 0.05$. Letters only presented when ANOVA indicated a significant effect

the increment of trunk area was also decreased in RDC-1 and RDC-2 compared to control trees. As a consequence of greater increment in canopy volume in the control hedgerow compared to both RDI treatments, more canopy volume must be extracted with hedging pruning in control hedgerows to achieve a similar post-pruning dimension (Table 2).

Shoot growth, bud development, and inflorescence characteristics

Across seasons and sides, irrigation regimes affected bud and inflorescence development significantly, rather than shoot length, internode length, or bud number (Table 3). The percentage of floral bud development increased 2.9-fold in both RDI-1 and RDI-2 compared to control. In contrast,

Table 3 Seasonal shoot length and axillary bud, flowering, and fruiting parameters in the whole plant and on both sides of olive hedgerows pruned laterally in alternate years and irrigated with control and two regulated deficit irrigation (RDI) during three growing seasons

Source of variation	Shoot characteristics						Inflorescence characteristics		
	Shoot length (cm)	Internode length (cm)	Axillary bud/shoot (#)	Floral bud (%)	Fruiting inflorescence (%)	Fruit/fruiting inflorescence (#)	Length (mm)	Total flower (#)	Perfect flowers (#)
Irrigation (I)									
Control	20.54	0.84	14.2	5.5 b	93.4	5.8 a	32.0	16.3	13.2 a
RDI-1	18.30	0.98	13.6	14.4 a	89.6	4.2 b	30.5	15.3	11.4 b
RDI-2	14.61	1.00	11.4	17.6 a	86.0	2.4 c	31.2	15.7	12.1 ab
Side (S)									
Unpruned	13.60 b	0.99	10.4 b	16.5 a	91.2	3.54	nd	nd	nd
Pruned	22.04 a	0.89	15.7 a	8.5 b	90.8	3.35			
Year (Y)									
2015–2016	24.59 a	0.61 c	17.2 a	3.2 b	84.4	3.26	34.5 a	17.3 a	15.3 a
2016–2017	15.50 b	0.93 b	11.4 b	27.2 a	87.3	3.85	29.4 b	15.7 b	9.9 c
2017–2018	13.37 b	1.29 a	10.5 b	7.1 b	99.9	3.19	29.9 b	14.3 c	11.5 b
P value									
I×S	0.532	0.113	0.102	0.070	0.613	0.869	–	–	–
I×Y	0.466	0.811	0.569	0.038	0.899	0.024	0.011	0.086	0.569

Values with the same letter are not significantly different within each year by LSD test at $P \leq 0.05$. Letters only presented when ANOVA indicated a significant effect

Nd no data

perfect flower per inflorescence and fruits per fruiting inflorescence were reduced 1.1- and 1.8-fold on average in RDI-1 and RDI-2, respectively, compared to control (Table 3).

Shoot growth and development varied significantly between pruned and unpruned sides (Table 3). Across seasons and irrigation regimes, shoots on unpruned sides were significantly shorter with lower bud number and higher percentage of floral buds with respect to shoots growing on pruned sides. Figure 3g, h shows average shoot elongation (2015–2016 to 2017–2018) and average floral bud percentage (spring 2016, 2017, and 2018) within either hedgerow side and for each irrigation treatment. Shoot growth on pruned sides was significantly reduced in RDI-2 compared to control, while it was intermediate in RDI-1. During the following seasons, bud floral percentage showed the opposite pattern: the highest in RDI-2, intermediate in RDI-1, and the lowest percentage in control (Fig. 3g). On unpruned sides, shoot growth and the percentage of bud induction for the following season were non-responsive to irrigation regimes (Fig. 3h).

Oil yield, oil yield components, and fruit characteristics

Fruit and oil yield, fruit weight, fruit water content, and fruit oil content were highly responsive to irrigation regime, although the response varied among seasons (i.e., significant irrigation by year interaction, Table 4). During 2015–2016, irrigation regimes showed no significant difference in production and fruit characteristics. In the second season, both RDI-1 and RDI-2 showed on average a fruit yield of 9.75 kg/tree, an oil yield of 1.5 kg oil/tree, and 5800 fruits per tree, significantly higher than control trees (5.9 kg/tree, 0.8 kg oil/tree, and 3827 fruits/tree, respectively). Fruit characteristics, however, were not affected by irrigation regimes with the exception of higher pulp/pit ratio in RDI-1 than in control (Table 4). In the third studied season, RDI-1 showed a significant increase in oil yield (1.8 kg oil/tree) and fruit number (5053 fruits/tree) compared with RDI-2 (0.8 kg oil/tree and 2024 fruits/tree, respectively) and control (0.2 kg oil/tree and 744 fruits/tree). At the same time, RDI-2 showed a significant increase in oil yield and fruit number compared to control. Fruits in RDI-1 were heavier with lower fruit water content than RDI-2 and control, while in RDI-1 and RDI-2, fruit oil concentration in both fresh and dry basis was higher than control. Across the three seasons, RDI-1 and RDI-2 showed oil yields of 1.64 and 1.37 kg oil/tree, significantly higher than control hedgerows (0.94 kg oil/tree). In addition, across seasons, RDI-1 and RDI-2 had similar water productivity of 9.9 and 10.7 kg of oil per mm of water applied, significantly higher than those 5.3 kg oil/mm of the control. Water productive differences between control and both RDI regimes increased as the experiment progressed (Table 4).

No significant interaction for oil yield and fruit characteristics was detected in hedgerow side by irrigation regime (Table 4). Regardless irrigation regime and season, unpruned sides produced 70% of the total fruit and oil of the whole hedgerow. Fruits on unpruned sides had lower pulp/pit ratio and were less mature at harvest than fruits on pruned sides. In contrast, fruit weight, fruit water content, and fruit oil concentration were similar on either side of the hedgerow, despite large fruit number differences.

Discussion

Plant water status response to RDI

In control hedgerows irrigation and rainfall replaced around 80% of ETc and SWP average were − 1.20 MPa during spring–early summer (Period I) and − 1.35 MPa during early summer–autumn (Period II). Control showed similar SWP values of − 1.2 MPa before and − 1.4 MPa after pit hardening, suggested for irrigation scheduling under non-water stress conditions in intensive olive orchards (300–500 trees/ha) (Moriana et al. 2012; Trentacoste et al. 2015b). Control irrigation maintained plant water status similar to the single SWP value of − 1.2 MPa proposed by Fernández et al. (2011) and Padilla-Díaz et al. (2016) for low water-deficit scheduling of young and adult narrow hedgerows. In addition, stomatal conductance of control hedgerows was more elevated than RDI treatments, although only occasionally significantly higher than RDI-2. Therefore, irrigation scheduling with a kc = 0.70 could have replaced full irrigation needs and overestimated the planned 70% ETc in the control treatment. These results imply that a kc around 0.55 (calculated in control treatment from water applied/ETo ratio, Table 1) could be more appropriate for the study conditions (olive narrow hedgerows and semiarid conditions) as proposed by López-Olivari et al. (2016).

In both RDI regimes, SWP decreased continuously from − 0.8 to − 1.0 MPa from bud break (mid-August) toward the end of shoot growth (mid-January) when SWP reached minimum values of ~ − 1.80 and ~ − 2.25 MPa in RDI-1 and RDI-2, respectively. According to SWP thresholds for olive hedgerows proposed by Fernández et al. (2011), water stress is moderate when: $-1.2 > \mathrm{SWP} > -1.7$ MPa and severe when: $\mathrm{SWP} < -1.7$ MPa. Across seasons, RDI-1 hedgerows were exposed to moderate and RDI-2 from moderate to severe water stress conditions during Period I. SWP descent was accompanied with a depletion in stomatal conductance significantly lower in RDI-2 than in control trees, in contrast to similar g_s in both RDI-1 and control. Thus, SWP was more responsive to moderate water stress than g_s, in relation with effective stomatal regulation widely described in olive trees (e.g., Moriana et al. 2012).

Table 4 Fruit and oil yield, fruit number, and characteristics in the whole plant and on both sides of olive hedgerows pruned laterally in alternate years and irrigated with control and two regulated deficit irrigation (RDI) during three growing seasons

Source of variation	Fruit yield (kg/tree)	Oil yield (kg/tree)	Fruit number (#/tree)	Fruit fresh wt (g)	Fruit dry wt (g)	FWC (%)	FOCFB (%)	FOCDB (%)	Pulp/Pit	MI	WP (kg/ha/mm)
2015–2016											
Control	12.4	1.8	8615	1.47	0.47	66.8	14.3	55.5	6.3	1.1	11.5 b
RDI-1	12.4	1.8	7201	1.80	0.60	67.2	14.4	55.7	6.8	1.2	13.8 ab
RDI-2	10.6	1.7	6156	1.70	0.60	61.1	14.7	53.2	6.3	1.2	16.3 a
2016–2017											
Control	5.9 b	0.8 b	3827	1.67	0.57	65.8	13.6	50.9	5.9 b	1.4	3.5 c
RDI-1	9.2 a	1.4 a	5307	1.90	0.67	64.3	15.5	54.4	7.2 a	1.6	7.6 b
RDI-2	10.3 a	1.6 a	6294	1.70	0.53	62.9	15.6	51.0	6.7 ab	1.3	11.1 a
2017–2018											
Control	1.8 c	0.2 c	744 c	2.40 b	0.80 b	66.0 a	11.5 b	42.9 b	6.4	1.2	0.8 c
RDI-1	11.3 a	1.8 a	5053 a	2.27 b	1.20 a	45.6 b	15.6 a	47.6 a	6.2	1.1	8.3 a
RDI-2	5.6 b	0.8 b	2024 b	2.80 a	0.87 b	69.2 a	14.5 a	47.3 a	6.2	1.2	4.9 b
Irrigation (I)											
Control	6.71 c	0.94 c	4395	1.84 b	0.61 c	66.2 a	13.1 b	49.8	6.2	1.2	5.3 b
RDI-1	10.95 a	1.64 a	5854	2.00 ab	0.82 a	59.0 b	15.2 a	52.6	6.7	1.3	9.9 a
RDI-2	8.84 b	1.37 b	4825	2.07 a	0.70 b	64.4 a	14.9 a	50.5	6.4	1.2	10.7 a
Side (S)											
Unpruned	5.98 a	0.88 a	3527 a	1.86	0.76	63.2	14.1	50.6	6.27 b	1.2 b	NA
Pruned	2.86 b	0.43 b	1498 b	2.03	0.85	63.2	14.7	51.4	6.61 a	1.3 a	
Year (Y)											
2015–2016	11.79 a	1.74 a	7324 a	1.67 b	0.56 b	65.0 a	14.5	54.8 a	6.5	1.2 b	13.9 a
2016–2017	8.48 b	1.28 b	5143 b	1.76 b	0.62 b	64.3 a	14.9	52.1 a	6.6	1.4 a	7.4 b
2017–2018	6.23 c	0.92 c	2607 c	2.49 a	0.96 a	60.3 b	13.9	45.9 b	6.2	1.1 b	4.7 c
P value											
I×Y	0.003	<0.001	0.0037	0.014	0.003	<0.001	0.152	0.478	0.099	0.177	0.002
I×S	0.451	0.330	0.8130	0.916	0.284	0.871	0.914	0.945	0.856	0.855	NA

Values with the same letter are not significantly different within each year or source of variation by LSD test at $P \leq 0.05$. Letters only presented when ANOVA indicated a significant effect

FWC fruit water content, *FOCFB* fruit oil concentration in fresh basis, *FOCDB* fruit oil concentration in dry basis, *MI* maturity index, *WP* water productivity, *NA* not applicable

When irrigation in RDI and control was the same after mid-January, SWP, g_s, and soil water content became similar in RDI-1 and RDI-2 to those recorded in control trees (Fig. 2). Rapid plant water recovery is consistent with previous studies in which olive trees with water potentials as low as −8.0 MPa keep their recovery capacity after rehydration (Trentacoste et al. 2018b; Boughalleb and Hajlaoui 2011). Rapid recovery of plant water status allowed for more effective management of deficit irrigation strategies. This is due to the fact that fruit oil accumulation occurred mainly during the water-deficit recovery period (Period II) with average SWP values of −1.35 and −1.60 MPa in RDI-1 and RDI-2, respectively. These values were higher than the SWP values of −1.5 to −2.0 MPa found by Gucci et al. (2007) and Rosecrance et al. (2015), above which fruit oil accumulation was scarcely reduced.

Vegetative growth and shoot development response to RDI

The vegetative growth period in olive trees is considered a high water-deficit sensitivity period in olive production because shoot growth and fruit number development occur simultaneously both for the present (flowering and fruit set) and the following season (bud number). For this reason, deficit irrigation strategies have generally been evaluated after a determination of fruit number. However, in super-high density olive hedgerows, where narrow alleys and tree spacing are used, lower vegetative growth can be an advantage to improve canopy illumination and yield (Gómez-del-Campo et al. 2017).

In the last two seasons, comparing the canopy increment of control hedgerows to the RDI treatments, width and height increment in RDI-1 was reduced 52% and 29% on average, whereas in RDI-2, it was reduced 79% and 25%, respectively (Table 2). These values are similar to those of previous studies in narrow olive hedgerows where deficit irrigation has been a useful tool for vegetative control (Rosecrance et al. 2015; Marra et al. 2016; Fernández et al. 2013). As a consequence of smaller hedgerow dimensions, winter pruning removed less canopy volume (and presumably biomass) to achieve target hedgerow sizes. After the third study season, in hedgerows irrigated with RDI-1 and RDI-2, canopy width was smaller than target width (1.2 m). Therefore, pruning may not be necessary for allowing passage of the harvesting machine (~ 1.2 m shaking chamber width).

With respect to measurements at shoot level, elongation varied following water application with values around 20.5, 18.3, and 14.6 cm in control, RDI-1, and RDI-2, respectively, but without a significant difference when target shoots on pruned and unpruned sides were averaged (Table 3). Within either side, shoot elongation was more water deficit responsive on pruned than on unpruned sides (Fig. 3g, h). On unpruned sides with higher fruit load (Table 3), shoot elongation seems to be more affected by fruit load than by water applied, in line with the results reported by Mezghani et al. (2012). Shoots growing on the unpruned side showed low floral bud percentage in the following growth season, regardless of irrigation treatment (Fig. 3h). In this sense, high fruit load can exert a hormonal inhibitory effect on bud induction as previously demonstrated (Lavee 2007). In addition, during the following season, bud induction percentage on unpruned sides was measured in the remaining canopy after pruning. Thus, bud induction as well as shoots growing in shade conditions could be reduced (Trentacoste et al. 2017).

On pruned sides with low fruit load (Table 3), vegetative control was more responsive to applied water (Fig. 3g). In control hedgerows, 1-year-old shoots were longer, with a higher node number, but with a lower percentage of floral buds than in RDI-2 hedgerows. In turn, on the pruned side, higher shoot growth in control compared to RDI hedgerows led to a decrease in fruit number the following season. Similarly, Albarracín et al. (2017) found a smaller fruit number in vigorous shoots as the result of more intensive mechanical pruning. Grattan et al. (2006) found in hedgerow orchards that inflorescence number increased during the following season after applying sustained deficit irrigation 15% and 25% ETc compared to 89% and 107% ETc. Trentacoste et al. (2018b) evaluating eight olive cultivars and three water regimes in a pot experiment found a negative relationship between inflorescence density and node number per shoot.

Thus, a possible explanation for the marked reduction in fruit number in control hedgerows as the experiment progressed may be that control hedgerows formed a higher proportion of watersprouts after hedging pruning compared to the RDI treatments. Watersprouts are characterized by high levels of gibberellin that act by inhibiting floral induction (reviewed by Fabbri and Benelli 2000). In a recent study, Albarracín et al. (2017) found that severe, rather than light, lateral pruning led to greater formation of non-productive watersprouts. However, further studies are required to understand the combined effect of vigor and radiation on floral induction.

It is worth highlighting that both unpruned and pruned sides within the same tree seem to have an autonomous behavior (Lavee 2007). Unpruned sides had heavy fruit load, low vegetative growth, and formed few inflorescences the following seasons. The opposite, pruned side had light fruit load which led to higher vegetative growth, and floral buds were not affected by the presence of fruit on the unpruned side.

With respect to flowering parameters, neither RDI strategy affected flower number per inflorescence, but rather decreased perfect flower number per inflorescence (Table 3). However, the perfect flower number was sufficiently high to achieve a similar percentage of fruiting inflorescences among treatments. The slight influence of water deficit on flower quality could result from the fact that most flowering parameters were already established when irrigation strategies had not yet reached a significant difference in plant water status (Fig. 2), i.e., 8 weeks before full bloom (Rapoport et al. 2012). In contrast, fruit number per fruiting inflorescence (i.e., fruit set) was progressively reduced with the reduction of water applied during Period I in relation with more evident differences in plant water status among treatments (Fig. 2).

Characteristics of yield and fruit response to RDI strategies

After the three studied seasons, RDI-1 and RDI-2 showed 174% and 146% higher oil yield than control, explained by both larger fruit number and more exposure of fruits to irradiance than control hedgerows. This became more evident in the last two seasons when control showed excessive and unproductive vegetative growth after mechanical lateral pruning. Across seasons, RDI-1 was 120% more productive than RDI-2, explained mainly by larger fruit number, as a consequence of the increase in the number of inflorescences developed and in fruit set (Table 3).

Fruits had higher oil content, lower moisture, and earlier maturity in both RDI treatments than in control. These differences among treatments may be attributed to the fact that fruits were more exposed to solar irradiance in both narrower RDI hedgerows than in control. Similar results were reported in a previous study conducted within the experimental orchard, where fruits were collected from a wide range of canopy positions with variable incident irradiance (Trentacoste et al. 2018a). In RDI regimes, larger fruit size and higher fruit oil concentration than in control occurred even when fruit number was larger, indicating that those yield components were primarily affected by source supply mediated by micro-environmental irradiance and not limited by sink competition (Trentacoste et al. 2015c). In another study, Caruso et al. (2017) found that fruit characteristics were more affected by fruit position within the canopy than by water regimes. In this work, however, lower plant water status reduced fruit weight and oil content in contrast with in our findings. Conflicting results can be explained by the fact that, in our study, water deficit was applied before pit hardening in contrast to Caruso et al. (2017) in which water deficit was applied after pit hardening when most of the fruit growth expansion and oil accumulation had already occurred.

The higher oil yield in RDI-1 and RDI-2 compared to control was achieved with 17% and 35% reduction in the total applied water (Table 1), which resulted in an increase in water productivity from 5.3 kg oil/mm in control to 9.9 and 10.7 kg oil/mm in RDI-1 and RDI-2, respectively. The trend of increasing yield per unit water under deficit irrigation has been widely reported in olive (e.g., Correa-Tedesco et al. 2010; Trentacoste et al. 2015b).

Conclusions

Previous studies have highlighted the importance of deficit irrigation strategies in super-intensive olive hedgerows to control vegetative vigor, improve irradiance environments, and increase oil production, oil quality, and water use efficiency (Hernandez-Santana et al. 2017; Marra et al. 2016; Rosecrance et al. 2015). However, in these studies, water-deficit strategies were applied when most vegetative growth had occurred, and therefore, only a slight or moderate vegetative control was obtained. In Argentina, olive trees express excessive vegetative growth, and consequently, require a high degree of canopy management.

The RDI-1 strategy, which applied moderate water stress during the shoot growth and fruit oil filling periods (maintaining SWP between − 1.2 MPa and − 1.7 MPa), was the most effective irrigation regime. RDI-1 controlled hedgerow dimensions and improved fruit microclimate, oil yield, and water productivity compared to hedgerows well-irrigated over the whole growing season. Furthermore, the RDI-2 strategy also reduced substantially vegetative growth on the pruned side and improved oil yield and water productivity compared to control. Oil yield in RDI-2, however, was lower than in RDI-1, which obtained an average yield of 2676 kg oil/ha over the 3-year period. This oil yield remained stable among seasons (between 2300 and 2900 kg oil/ha), which allowed a more effective control of vegetative growth after pruning in each season. This study also demonstrated that hedgerows managed by combining severe annual lateral pruning with non-water deficit developed shoots with low bud fertility that shaded the fruits formed within the canopy, leading to a marked reduction in oil yield with the passing of seasons.

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