



The effect of water status on productive and flowering variables in young ‘Arbequina’ olive trees under limited irrigation water availability in a semiarid region of Chile

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Abstract

The intense drought affecting olive production in Northern Chile underscores the need to research non-traditional irrigation strategies to obtain the best crop performance. Accordingly, this study aimed to obtain preliminary data to guide future research on this topic. Different water replenishment levels on crop evapotranspiration (ET_c ; 13.5, 27.0, 40.5, and 54%) were established in a young orchard, cv. Arbequina, from the end of fruit drop (EFD) to full bloom in the next season. We evaluated the influence of plant water status (Ψ_{stem}) and crop load, considered as function of fruit number divided by trunk cross-sectional area, on reproductive and productive variables using multiple linear regressions. Our results show that crop load and Ψ_{stem} measured from EFD to harvest affected yield components. Nevertheless, Ψ_{stem} had the strongest influence on fruit size, pulp development, oil accumulation, and yield. Oil content and yield were reduced by 54% and 50% for each MPa, respectively, from $\Psi_{stem\ EFD-H} - 1.8$ MPa, an effect that intensified as crop load increased. During the period of flower development (September–November), the number of flowers per inflorescence and percentage of perfect flowers were reduced when Ψ_{stem} was less than -2.0 MPa. These preliminary results showed that bud differentiation, inflorescence and flower formation are highly sensitive to water deficit.

Keywords Deficit irrigation · Flowering · Oil yield · Stem water potential · Water relations · Water use efficiency

1 Introduction

Chile is an emerging competitor in olive oil production. One of its main olive growing areas is the Coquimbo region, with 21% of the country’s planted area. The region has an arid climate, with a high accumulation of degree-days (1600–2100; base 10 °C), is frost-free, and has an annual rainfall of 75–100 mm, mainly concentrated in winter (Uribe et al. 2012). Under these conditions, and with irrigation doses of about 8000 m³ ha⁻¹, yield potential in full production is between 12 and 15 t ha⁻¹ (Tous et al. 2014). However, during the last 8 years, limited irrigation has been a major

issue for olive farmers. This is caused by a consistent drop in water availability in irrigation dams and groundwater, resulting from a progressive decrease in precipitation. A reduction between 20 and 30% towards the middle of the 21st century is estimated, possibly as a response to global warming and a greater competition for water from other sectors (Santibáñez et al. 2014). Thus, the prolonged and intense drought affecting the Coquimbo region makes it impossible to satisfy fruit tree water demand. The productive potential is reduced under these conditions, making it necessary to develop irrigation management strategies under conditions of limited irrigation water availability.

Variables used to assess the efficiency of different irrigation strategies include irrigation water use efficiency (IWUE), expressed as kg of fresh fruit or kg of oil per mm of water supplied per hectare (Trentacoste et al. 2015). This information is essential in areas where water is scarce and expensive, such as the Coquimbo region, where the production-related cost/benefit ratio must be evaluated. Several studies have shown a curvilinear olive yield response to the amount of water irrigation supply (Moriani et al.

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2003; d'Andria et al. 2004; Berenguer et al. 2006; Grattan et al. 2006; d'Andria 2008), where maximum oil yield was achieved when water applied was close to 60–75% of the crop evapotranspiration, and a higher IWUE was reached with low levels of applied water.

Moriana et al. (2012) reported that measurements of plant water status enable a good approximation of irrigation needs, generating water potential thresholds within which a good yield can be reached, regardless of the location. These authors indicated that water potential must be kept over -1.2 MPa and -1.4 MPa before and after pit hardening, respectively, to maintain olive trees in non-stress condition. Likewise, Trentacoste et al. (2015) found that, regardless of tree density and climate conditions, the non-stress threshold in cv. Frantoio was -1.3 MPa and -1.5 MPa before and after pit hardening, respectively. By contrast, Naor et al. (2013) described this threshold as dependent on the crop load. These authors observed that oil yield in cv. Koroneiki was not affected by levels of water stress applied during the period of oil accumulation (-1.5 MPa to -4 MPa) when the crop load was low. However, with high crop loads, there was greater oil yield dependence on water stress levels, associated with a high demand of assimilates. Thus, olive yield response to water status is related to intensity, duration and moment of stress (Moriana et al. 2012), and their interaction with crop load (Martín-Vertedor et al. 2011; Naor et al. 2013).

Although olive trees respond positively to a lower percentage of ET_c replenishment, water stress during critical periods, such as the flowering process, affects yield (Rapoport et al. 2012; Pierantozzi et al. 2013) mainly by a reduction of crop load (Ben-Gal et al. 2011). Under Mediterranean climatic conditions, where olive trees are traditionally grown, rains in winter and early spring frequently provide sufficient water to the soil for optimal development in the differentiation process, flower development, and shoot growth. Therefore, the effect of reduced water availability during this period of great sensitivity to water stress has been of little interest (Connor and Fereres 2005; Rapoport et al. 2012; Pierantozzi et al. 2013). In addition, most studies focused on different levels of reduction in irrigation supply between specific phenological periods, and establish non-stress conditions before and after specific study periods (Gómez-del-Campo 2013a, b; Naor et al. 2013; Pierantozzi et al. 2014). Nevertheless, under severe drought conditions water availability is reduced for a longer time, with the distribution of scarce water in key moments becoming more important to ensure a minimum production and preserve the orchard life.

In this context, this study aimed to develop a preliminary evaluation on irrigation management strategies for olive crop under limited irrigation water availability, by (1) exploring the influence of plant water status from the end of fruit drop

to the next season's full bloom, considering crop load on plant production variables; and (2) comparing the yield and irrigation water use efficiency for oil production using low ET_c replenishment levels in a young orchard of 'Arbequina' olive trees.

2 Materials and methods

2.1 Site and orchard characteristics

The study was carried out from December 2012 to November 2013 in a commercial 4-year-old 'Arbequina' olive orchard planted in 2008, belonging to Valle Arriba S.A. and located at Tabalí, 15 km from Ovalle in the Limarí province, Coquimbo region, Chile ($30^{\circ}39'S$, $71^{\circ}25'W$). The experimental plot is part of the Tabalí soil series, characterized by alluvial terraces, varying from flat to rolling lands (IREN 1964). The clayey soil (ISSS classification) contains 52% clay, 30.5% sand, and 17.5% silt, a bulk density of 1.1 Mg m^{-3} , with gravimetric water content at field capacity of 32.8% (-0.03 MPa) and 22% at the permanent wilting point (-1.5 MPa). The average root depth observed was 0.65 m. The olive trees were planted in an east–west orientation on hedgerows with a 6×3 m spacing. Their harvest in the previous season was 3500 kg ha^{-1} .

2.2 Irrigation treatments

Prior to this study, the orchard was fully irrigated. From the last week of December 2012 (end of fruit drop) to November 2013 (full bloom), different irrigation treatments were carried out based on crop evapotranspiration (ET_c) replenishment levels of 13.5, 27.0, 40.5, and 54.0%. The ET_c was calculated with Eq. (1), using reference evapotranspiration (ET_o) calculated by the Penman–Monteith method (Allen et al. 1998), and a crop coefficient (K_c) of 0.7 (Girona et al. 2002), which was adjusted by a factor dependent on the coverage (K_r) (Fereres et al. 1981; 2012). The K_r was estimated as the average daily fraction of the intercepted photosynthetically active radiation ($fPAR_i$), described below, obtaining an average intercepted fraction of 0.35 for all trees. This value was used throughout the study.

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

Irrigation was supplied with a double-irrigation dripper line with emitters spaced 1 m apart (6 emitters per tree) delivering 4, 3, 2, and 1 l h^{-1} (depending on the treatment). Irrigation scheduling was the same for all treatments and determined based on orchard water availability. Thus, from mid-December (beginning of treatments) until early March, weekly irrigations were carried out. Later, irrigations were scheduled every 15 days (Fig. 2). Total

irrigation from the beginning of the treatment until harvest was 74.6, 56, 37.3 and 18.65 mm for the treatments of 54, 40.5, 27 and 13.5% ET_c, respectively. Finally, in October 2013 a single irrigation was applied (Fig. 2). The irrigation time was the same for all treatments.

2.3 Meteorological data

During the study, maximum and minimum temperatures, relative humidity, precipitation, solar radiation, vapor pressure deficit, and wind speed were recorded through a weather station (Campbell Sci; Utah, USA) located 1 km from the study site.

2.4 Fraction of intercepted solar radiation ($fPAR_i$)

The $fPAR_i$ was calculated (Eq. 2) by measuring the radiation not intercepted by the trees (PAR_{ni}) along with the incident radiation on the orchard (PAR_o) on a completely sunny day at the beginning of the study. The PAR measurements were taken with a SunScan SS1 ceptometer (Delta-T Devices Ltd., Cambridge, UK) in the area assigned under the canopy of the tree in the center of each plot. Measurements were taken every 0.5 m cross-sectionally to the row (42 measurements per tree), capturing the shaded and non-shaded areas on the entire surface of the soil assigned to the tree (PAR_{ni}). They were taken five times during the day: at solar noon, two, and four hours before and after solar noon. Immediately before taking the measurements under the canopy, the incident PAR (PAR_o) was measured in a non-shaded area without canopy interference, at a height of 1.5 m.

$$fPAR_i = \text{daily average of } [(PAR_o - PAR_{ni})/PAR_o]. \quad (2)$$

2.5 Plant water status

Stem water potential was measured at pre-dawn (Ψ_{pd}) and midday (Ψ_{stem}) as indicators of plant water status (Moriana et al. 2012). In both measurements, one small branch per tree was selected from the central part of the canopy under direct sun exposure. To measure Ψ_{stem} , branches were covered with bags of aluminum sheets wrapped in plastic at least 1 h before taking the measurements to allow the leaf water potential to balance with the stem water potential (Trentacoste et al. 2015). Ψ_{pd} and Ψ_{stem} were measured between 5:30–6:00 a.m. and 12:30–1:30 p.m., respectively, once a week until February 2013, then once a month. Measurements were taken according to the procedure described by Guerfel et al. (2009). A Scholander pressure chamber (PMS Model 600, USA) was used for the measurement.

2.6 Yield and yield components

Olives were harvested on May 6, 2013. From a 2-kg sample per tree, 100 fruits were weighed to determine their average weight (wt). Total fruit number per tree was estimated from the average fruit weight and total harvest weight. Fruit yield and crop load efficiency per tree were expressed dividing the total harvest weight and fruit number, respectively, by the trunk cross-sectional area (TCSA) measured 30 cm above the soil at harvest, to account for possible differences in tree size. Oil concentration in the pulp was determined by the Soxhlet method (AOAC 2000) with a sample of 25 fruits per tree. The pulp was dried in an atmospheric pressure oven at 70 °C, until achieving a constant weight. The result was expressed in percentage of oil pulp based on dry matter. Percent water concentration was calculated as $100 \times (\text{fresh wt} - \text{dry wt})/\text{fresh wt}$. Oil yield efficiency at harvest (kg oil cm^{-2} of TCSA) was calculated per tree according to the following equation:

$$\text{Oil yield efficiency} = (\%OCM) \times (DW/FW) \times (M/F) \times (P) \quad (3)$$

where OCM is the pulp oil concentration on a dry-weight basis, DW/FW is the dry-to-fresh-weight ratio, M/F is the fresh mesocarp/fruit ratio, and P is the fruit yield efficiency in kg cm^{-2} TCSA per tree. Irrigation water use efficiency for oil yield ($IWUE_o$) was estimated as the kg of oil per mm of irrigation per hectare applied from the beginning of the treatments to harvest.

2.7 Shoot growth and flower development

Shoot growth was measured monthly in three fruitless shoots per tree, from the beginning of treatments (end of December 2012) until harvest (first week of May 2013). The number of flowers per inflorescence and the percentage of perfect flowers were determined in full bloom (November 1, 2013), when 70% of the inflorescences showed at least 50% open flowers (Sanz-Cortés et al. 2002). To count the number of flowers per inflorescence, a sample of 20 inflorescences per tree (2 inflorescences \times 10 branches) was selected from the middle third of each branch located at the center of each side of the hedgerow. Then, the percentage of perfect flowers present in each inflorescence was determined. A flower was considered perfect when it presented both functional androecium and gynoecium, and staminate when it only had stamens or showed an atrophied gynoecium (without development).

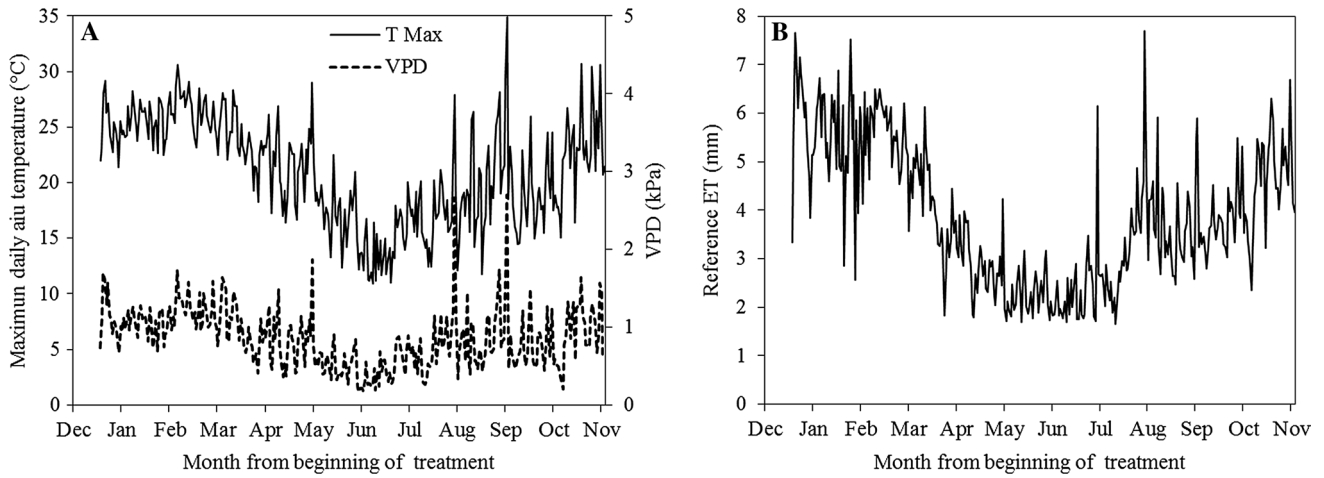
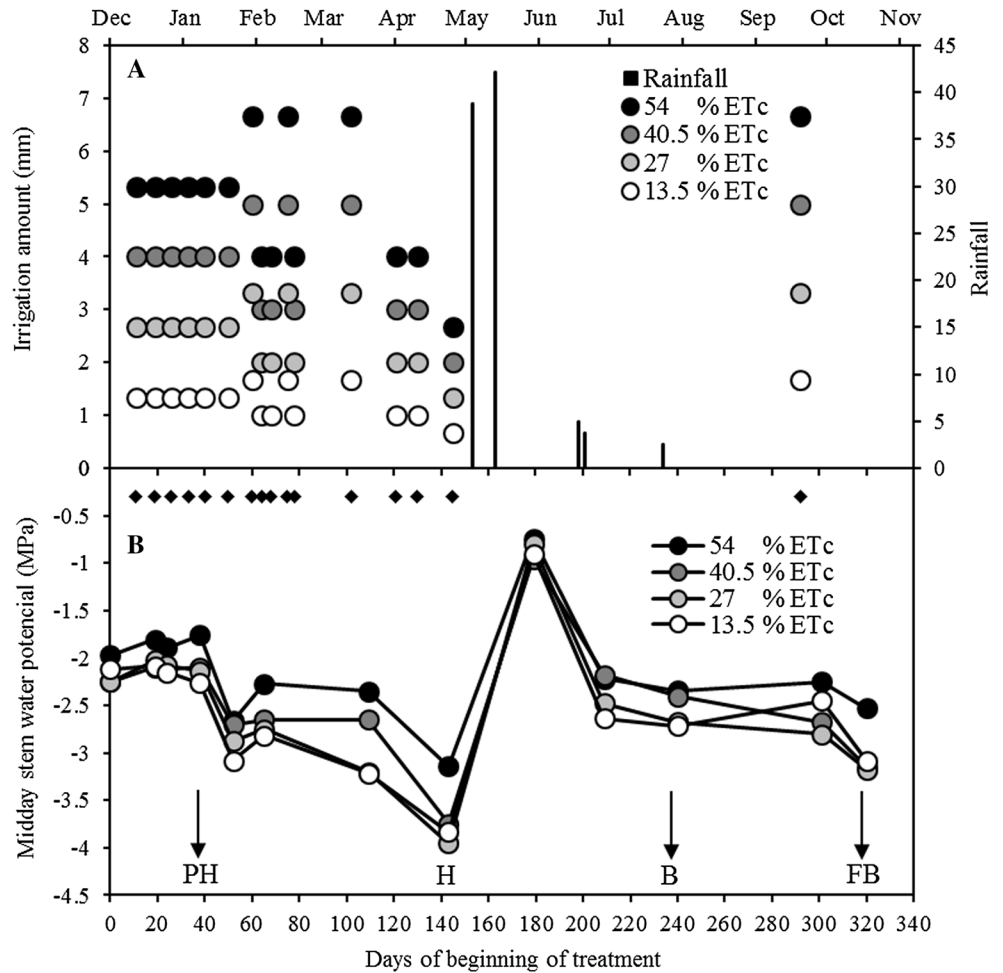


Fig. 1 a Seasonal daily maximum air temperature and vapor pressure deficit (VPD). b Seasonal daily reference ET_0 from end of fruit drop to full bloom of next season in Ovalle, 2012–2013. Bloom occurs

at mid-November; oil accumulation starts at the end of January, and harvest occurs in mid-May

Fig. 2 Irrigation amount (a) and midday stem water potential (b) in the irrigation levels (% of reference ET_c) from end of fruit drop to full bloom of next season. Diamond symbols indicate daily irrigation. PH pit hardening, H harvest, B budbreak, FB full bloom. Each data point represents a mean ($n=3$)



2.8 Experimental design and statistics

Homogeneous trees were selected in full bloom based on flowering, vegetative development (coefficient of variation for TCSA and $fPAR_1$ of 13% and 21%, respectively), vigor, height (~2.2 m), and health (no visible nutritional or pathological problems). However, high variability in crop load was observed at harvest. Therefore, crop load was expressed as fruit number per cm^2 of TCSA to normalize for tree size (Bustan et al. 2016). A randomized complete block design was used, considering the row as a block (three blocks). The experimental plot of each treatment consisted of three trees, with the central plant used as the experimental unit, and two other trees used as borders between treatments, to avoid any influence between neighboring treatments.

Simple and multiple regression models were adjusted for each variable evaluated as a function of average Ψ_{stem} between phenological periods, which were determined according to Sanz-Cortés et al. (2002), and crop load. Phenological periods were: end of fruit drop to pit hardening (EFD-PH), end of fruit drop to harvest (EFD-H), pit hardening to harvest (PH-H), harvest to budbreak (H-B), and budbreak to full bloom (B-FB). A *t* test was used for individual coefficients on the regression parameters estimated with a 5% level of significance. For model selection, both the Akaike (AIC) and the Bayesian (BIC) information criteria were assessed (Yang 2005). Mallows's *C_p*-statistic was used as an indicator of the contribution of the regressor variables in the fit regression models (Balzarini et al. 2008). To visualize the association between regressor variables, the relationship between the response and the other regressors was removed, then a partial residual analysis was performed with scatter plots (Draper and Smith 1998). The statistical program used was InfoStat v. 2013 (Di Rienzo et al. 2013).

3 Results and discussion

3.1 Seasonal conditions

The average maximum temperature from the beginning of the study until harvest was 24.5 °C, and the average vapor pressure deficit (VPD) was 1 kPa, with a mid-summer maximum of 1.87 kPa (Fig. 1). During the spring of 2013, the average maximum temperature was 20.6 °C (Fig. 1). Over the study period, there were no temperatures below 2.8 °C (data not shown). Maximum reference evapotranspiration (ET_0) in the summer was 7.6 mm day^{-1} . There was no precipitation during the summer, whereas in winter (end of May 2013) there were two important consecutive precipitation events of 39 and 42 mm day^{-1} (Fig. 2), leading experimental plots to field capacity and olive trees with optimal water status (Fig. 2).

3.2 Plant water status

Pre-dawn leaf water potential (Ψ_{pd}) for different phenological stages is detailed in Table 1. The Ψ_{pd} at the beginning of the study was similar among irrigation treatments, varying between –0.62 and –0.85 MPa. Pre-dawn values during the first eight weeks after bloom should be over –2.0 MPa and –3.0 MPa according to Costagli et al. (2003) and Rapoport et al. (2004), respectively, for optimal early fruit growth without significant reduction in cell number or cell size. In this study, average midday Ψ_{stem} among treatments was –2.11 MPa (Fig. 2), consequently olive trees were already stressed according to the ranges proposed previously (Moriani et al. 2012; Trentacoste et al. 2015). Before pit hardening, similar pre-dawn and midday water potential among treatments was largely due to the high capacity of the olive tree to extract water, even under water stress conditions (Sofa et al. 2007). During pit hardening, both soil and plant water status were significantly different among treatments (Table 1 and Fig. 2). The

Table 1 Pre-dawn leaf water potential at different phenology stages in 'Arbequina' olive trees irrigated with different water levels (% reference ET_c) from end of fruit drop to full bloom of next season ($n=3$)

Irrigation level (% ET_c)	Phenology stage					
	End of fruit drop	Pit hardening	Harvest	Midwinter	Budbreak	Bloom
	16-12-2012	23-01-2013	08-05-2013	13-06-2013	13-08-2013	01-11-2013
Ψ_{pd} : pre-dawn leaf water potential (MPa)						
54%	–0.62 ^y	–0.99 a ^z	–2.20 a	–0.60 ^y	–1.90 ^y	–2.03 a
40.5%	–0.85	–1.10 ab	–2.83 ab	–1.02 ^y	–2.15 ^y	–2.75 b
27%	–0.78	–1.30 bc	–3.13 b	–0.63 ^y	–2.17 ^y	–2.77 b
13.5%	–0.67	–1.52 c	–3.20 b	–0.80 ^y	–2.22 ^y	–2.62 b

^zDifferent letters indicate significant differences ($p \leq 0.05$) within columns according to the LSD test

^yNot significant

13.5% ET_c treatment showed the lowest Ψ_{pd} (-1.52 MPa), whereas the other irrigation treatments increased pre-dawn leaf water potential when irrigation contribution increased (Table 1). At harvest, the trees showed increased stress levels, which were greater in treatments with 40.5, 27, and 13.5% ET_c replenishment (average Ψ_{stem} -3.8 MPa) compared to the 54% ET_c (Ψ_{stem} -3.0 MPa). It should be noted that the two lowest irrigation rates were similar in terms of Ψ_{stem} over the study period; therefore, plant water status was similar between the 27% ET_c and 13% ET_c treatments.

Winter rains improved soil water status, rehydrating the olive trees (Fig. 2). However, at the onset of budbreak the Ψ_{pd} was between -1.9 and -2.22 MPa (Table 1), and stem water potential was lower than -2.0 MPa, with non-significant differences among treatments. Finally, during the period of flower development until bloom, Ψ_{stem} varied around -2.25 MPa at the highest replenishment irrigation

rate, whereas the other treatments reached an average Ψ_{stem} of -3.1 MPa.

3.3 Oil yield and yield component responses

As previously reported, crop load has a strong influence on water tree requirement (Bustan et al. 2016), shoot growth (Dag et al. 2010), yield and yield components, i.e., oil content and fruit size (Trentacoste et al. 2010). In this context, and given the variability of the crop load on the evaluated trees (variation coefficient of 33.1% Table 3), multiple linear regressions were adjusted, accounting for the crop load and water status of olive trees (Table 2). A slightly better fit (5%) in the adjusted models was found, considering the water potential of EFD-H vs. PH-H period (data not shown). Although there was a better fit considering Ψ_{stem} EFD-H, i.e., when different irrigation regimens began, a greater contribution of water status to the yield and its components was

Table 2 Regression coefficients and statistics obtained from linear explanatory models for productive and vegetative variables as a function of water status [expressed as mean midday Ψ_{stem} (MPa)], and

crop load [expressed as trunk cross-sectional area (fruits cm^{-2})], in 'Arbequina' olive trees irrigated with different water levels (% reference ET_c) from end of fruit drop to full bloom of next season ($n=12$)

Model ^z	Variable	Coefficient	<i>p</i> value variable	Mallows's <i>C_p</i>	R ²	<i>p</i> value model
Fruit weight (g fruit ⁻¹)	Constant	3.16	< 0.0001			
	Ψ_{stem} EFD-H	0.69	< 0.0001	71.2	0.88	< 0.0001
	Crop load	-2.30×10^{-3}	< 0.0001	40.0		
Pulp/fruit ratio	Constant	1.03	< 0.0001			
	Ψ_{stem} EFD-H	0.12	0.0007	22.3	0.71	0.0011
	Crop load	-4.5×10^{-4}	0.0042	14.0		
Fruit yield efficiency (kg cm^{-2} TCSA)	Constant	0.36	< 0.0001			
	Ψ_{stem} EFD-H	0.12	< 0.0001	49.4	0.95	< 0.0001
	Crop load	7.1×10^{-4}	< 0.0001	71.8		
Oil concentration dry weight basis (%)	Constant	102.63	< 0.0001			
	Ψ_{stem} EFD-H	21.08	0.0001	32.3	0.76	0.0004
	Crop load	-0.05	0.0031	15.1		
Water concentration (%)	Constant	86.15	< 0.0001		0.76	< 0.0001
	Ψ_{stem} PH-H	12.18	< 0.0001			
Oil content (g/fruit)	Constant	0.58	< 0.0001			
	Ψ_{stem} EFD-H	0.13	0.0017	32.1	0.81	0.0003
	Crop load	-5.80×10^{-4}	0.0003	19.5		
Oil yield efficiency (kg cm^{-2} TCSA)	Constant	0.05	0.0004			
	Ψ_{stem} EFD-H	0.02	0.0029	16.8	0.80	0.0006
	Crop load	4.8×10^{-5}	0.0247	8.6		
IWUE _o (kg mm^{-1} ha ⁻¹)	Constant	-48.00	0.0244			
	Ψ_{stem} EFD-H	-18.32	0.0156	11.1	0.70	0.0279
	Crop load	0.06	0.0198	10.7		
Shoot growth (cm)	Constant	8.5	0.0013			
	Ψ_{stem} EFD-H	2.05	0.0118	10.67	0.53	0.0222
	Crop load	-0.7×10^{-2}	0.0393	7.19		

TCSA trunk cross-sectional area (cm^2), IWUE_o irrigation water use efficiency for oil yield, EFD end of fruit drop, H harvest, B budbreak, B full bloom

^z Ψ_{stem} : stem water potential (MPa)

Table 3 Data characterization according to productive and vegetative variables and mean stem water potential (n = 12)

Variables ^z	Mean	Minimum	Maximum	CV
Shoot growth (cm)	2.1	1.0	4.2	47.4
Fruit weight (g fruit ⁻¹)	1.0	0.7	1.4	18.7
Pulp/fruit ratio	0.7	0.6	0.7	6.21
Oil concentration dry weight basis (%)	41.6	35.7	51.7	12.9
Oil content (g fruit ⁻¹)	0.14	0.07	0.24	36.0
Fruit yield (kg tree ⁻¹)	6.2	2.8	10.2	39.8
Oil yield (kg tree ⁻¹)	0.74	0.41	1.20	38.9
Fruit yield efficiency (kg cm ⁻² TCSA)	0.21	0.10	0.31	32.2
Oil yield efficiency (kg cm ⁻² TCSA)	0.03	0.01	0.04	29.3
IWUEo (kg oil mm ⁻¹ ha ⁻¹)	9.62	5.50	18.03	54.3
Crop load (fruits cm ⁻² TCSA)	201	89	305	33.1
Ψ_{stem} EFD-PH	-2.1	-2.5	-1.7	10.0
Ψ_{stem} EFD-H	-2.4	-2.9	-1.8	12.2
Ψ_{stem} PH-H	-2.8	-3.4	-1.9	15.0
Ψ_{stem} B-FB	-2.5	-3.1	-2.0	12.1

^zCV: coefficient of variation (%); IWUEo: irrigation water use efficiency for oil yield; Ψ_{stem} (MPa); TCSA: trunk cross-sectional area (cm²); EFD: end of fruit drop; PH: pit hardening; H: harvest; B: budbreak; FB: full bloom

observed after pit hardening. It has been widely reported that the least responsive period to water stress in olive is the EFD-PH period (Goldhamer 1999; Alegre et al. 2002; Lavee et al. 2007; Gómez-del-Campo 2013a, b). Indeed, Gómez-del-Campo (2013a, b) found in olive hedgerows of cv. Arbequina that water can be saved in this period until a Ψ_{stem} threshold of -2.9 MPa without any yield penalty. In the present study, Ψ_{stem} EFD-PH ranged from -1.7 to -2.5 MPa (Table 3), which was higher than the Ψ_{stem} threshold indicated by Gómez-del-Campo (2013a, b). Although stress intensity is relevant, stress duration also plays an important role (Moriana et al. 2012); therefore, it is likely that this

slightly better fit found throughout the period is due to stress duration.

The multiple linear regression analyses showed that plant water status, measured as Ψ_{stem} EFD-H, was the variable that most negatively affected fruit size, pulp development (pulp/fruit ratio), oil accumulation (oil concentration and content in the pulp), and yield (higher Mallows’s Cp value, Table 2). In turn, linear regression coefficients (slope) related to water potential showed a significantly higher impact on oil content and oil yield (kg of oil cm⁻² TCSA), which decreased from Ψ_{stem} EFD-H - 1.8 MP by 54% and 50% for each MPa, respectively (Tables 2, 3). The partial residuals of all multiple

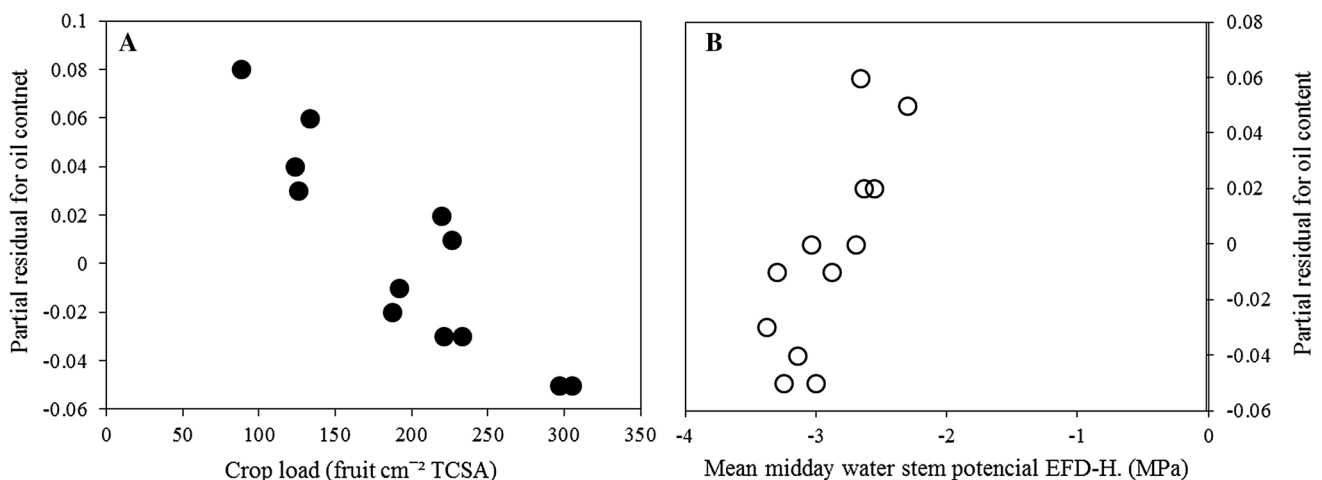


Fig. 3 Partial residuals for oil content as a function of **a** crop load (fruit/trunk cross-sectional area) and **b** average midday water potential from end of fruit drop (EFD) to harvest (H), corresponding to a multiple linear regression model (n = 12)

regressions showed that yield and its components were correlated linearly to crop load and water potential in the ranges of both variables (Fig. 3); therefore, it was not necessary to fit more complex models (e.g. polynomials). Although crop load (range from 89 to 305 fruits cm^{-2} of TCSA, Table 3) also influenced the reduction in productive traits due to deficit irrigation, its contribution was smaller (lower Mallows's C_p value, Table 2). This may be because (1) severe water stress affects mesocarp weight, in both cell size and number, whereas crop load mainly affects mesocarp weight through cell number (Gucci et al. 2009; Lodolini et al. 2011); and (2) photoassimilate synthesis and partitioning were more limited by water stress rather than by competition among sinks. In this scenario, there is a greater dependency on irrigation to achieve higher yields, despite olive trees being young and with high levels of crop load. This agrees with Martín-Vertedor et al. (2011) and Naor et al. (2013), who indicate that the impact of water stress on oil yield and quality increases with crop load.

Previous studies have indicated that reductions in irrigation rates during the summer can improve fruit water concentration with a consequent higher oil extractability, without a significant effect on oil yield (Goldhamer 1999; Alegre et al. 2002). In contrast, Girona et al. (2002) and Grattan et al. (2006) observed a lower oil production with summer irrigation deficits. In our study, we found that fruit water concentration was strongly correlated to water potential ($R^2 = 0.76$), decreasing by 12% for each average MPa reduction from pit hardening to harvest (Table 2). Furthermore, crop load had a non-significant effect, as previously reported (Trentacoste et al. 2010). Although fruit water concentration decreased as water stress increased, both oil concentration and content were affected, decreasing 21% and 0.13 g fruit $^{-1}$ for each $\Psi_{\text{stem EFD-H}}$ MPa, respectively (Table 2). The Ψ_{stem} range of olive trees varied between -1.9 and -3.4 MPa

in PH-H, i.e. a moderate stress according to Moriana et al. (2002). The slopes of these correlations could be important for designing irrigation strategies for greater productivity.

In this context, an irrigation threshold of $\Psi_{\text{stem EFD-H}}$ greater than -2.0 MPa must be maintained to avoid affecting yield components, in agreement with Gómez-del-Campo (2013a, b), although this threshold also depends on the crop load (Naor et al. 2013). However, reducing fruit water concentration requires values of $\Psi_{\text{stem PH-H}}$ less than -2.0 MPa. Puertas et al. (2012) found that a $\Psi_{\text{stem PH-H}}$ of -1.65 MPa did not affect fruit water concentration, yield components or extractability, but allowed for a 16% water saving. Further research is needed to determine the moment and degree of pre-harvest stress and when water concentration could be reduced, to improve extractability without affecting oil yield.

3.4 Irrigation water use efficiency

Oil yield was correlated to irrigation rates through a polynomial quadratic curve (Fig. 4). The highest level of ET_c replenishment (54% ET_c), generated the greatest yield, which was practically twice that of the other treatments. A similar response was found by Lodolini et al. (2016), who reported that a positive effect on yield could only be reached when irrigation supply was over 35% ET_c . For the lowest irrigation rates, no reduction in oil yield was observed. Irrigation water use efficiency ($IWUE_o$) for oil yield had the inverse response, i.e., the lowest irrigation rate was the most efficient, showing twice the efficiency of the other irrigation levels, whereas no distinction was seen at the highest irrigation rate (Fig. 4b). On the other hand, the multiple linear regression analysis showed that $IWUE_o$ was linearly and positively correlated to the crop load and the degree of stress increased ($\Psi_{\text{stem EFD-H}}$), with both variables contributing similarly to $IWUE_o$ (Table 2). This would explain

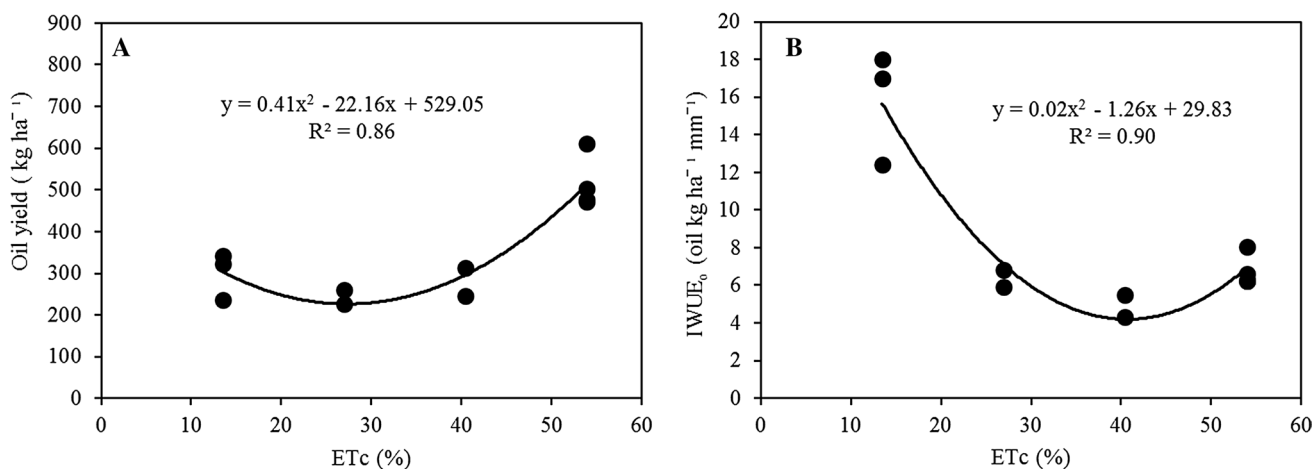


Fig. 4 a Oil yield and b irrigation water use efficiency for oil yield ($IWUE_o$) as a function of olive tree evapotranspiration ($n = 12$)

why the three lowest irrigation rates did not show any differences in yield among them, due to highly efficient water use of the trees under scarce availability (Trentacoste et al. 2015). In addition, these relations underscore the importance of increased irrigation rates when the crop load is greater, as $IWUE_o$ is positively associated with fruit number. However, it is necessary to assess a strategy of severe, long term water restriction. Although $IWUE_o$ increases, it may affect the olive tree reserves, and therefore, reduce the productive life of the orchard (Bustan et al. 2011).

3.5 Shoot growth and inflorescence response

In the Coquimbo region, most of the shoot growth occurs from the beginning of the season in August until January (Fichet and González 2011), which is why severe water stress is not desirable during this period (Naor et al. 2013). The soil water content in these months, from winter and spring rains (65 mm August 2012; data not shown), in addition to the increased water availability for irrigation due to snowmelt from the Andes, was sufficient for optimal shoot growth (Fig. 5). It has been shown that, depending on the stress severity, regulated deficit irrigation (RDI) during the summer could severely affect bud induction, when photosynthesis is affected (Alegre et al. 2001). However, in the present study we observed that, regardless of the treatment, more than 90% of the buds that developed in the 2012 spring–summer were floral buds in 2013 (Fig. 5). This occurred despite the fact that the Ψ_{stem} in the induction period (mid-January to the end of February) fluctuated between -2.0 and -3.0 MPa (Fig. 2). It is worth noting that, although shoot length was negatively affected by $\Psi_{stem\ EFD-H}$ and crop load (Table 2), the maximum

magnitude of this growth was only 4.2 cm (Table 3), which is why the effect of the irrigation levels on potential flower sites in the next season was minimal. This result may be because shoot growth rate in this period is low (Fichet and González 2011). Secondly, less shoot growth can be expected under Ψ_{stem} less than -2.0 MPa as observed during this period, according to Ψ_{stem} thresholds reported in previous studies (-1.8 MPa, Gómez-del-Campo et al. 2008; -2.0 MPa, Moriana et al. 2012; -1.3 MPa, Gómez-del-Campo 2013a, b).

Additionally, according to Rapoport et al. (2012), water restriction during flower development (elongation and branching of the inflorescence axis, and formation of the individual flower) significantly reduced inflorescence structure and quality (i.e. flowers per inflorescence, number and proportion of perfect flowers, and ovary quality). Similarly, it was observed that the average Ψ_{stem} from budbreak to full bloom ($\Psi_{stem\ B-FB}$) had a strong impact on the percentage of perfect flowers ($R^2=0.80$; $p<0.0001$) and on flowers per inflorescence ($R^2=0.72$; $p<0.0001$), where flowers per inflorescence decreased linearly from 20 to 0 as $\Psi_{stem\ B-FB}$ decreased from -2.0 MPa to -3.0 MPa (Fig. 6a, b). Also, Pierantozzi et al. (2014) observed that irrigation with 75% ET_c and average Ψ_{stem} greater than -2 MPa during flower development did not affect either flower number per inflorescence or the yield in a year with heavy flowering. In contrast, in a year with low flowering, trees that presented a water potential lower than -3.0 MPa bore similar fruit loads to those that presented water potentials above -1.5 MPa, although shoot growth did decrease with low Ψ_{stem} . Therefore, irrigation thresholds between -1.3 and -1.5 MPa (as a safety factor) can be used during the spring without affecting reproductive variables, but partially reducing shoot growth,

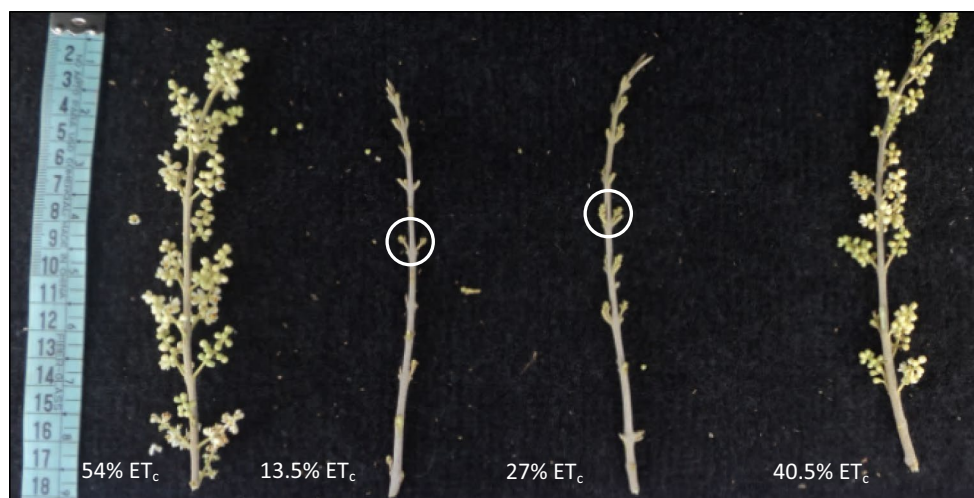


Fig. 5 Representative samples of flowering shoots at bloom in ‘Arbequina’ olive trees irrigated with different water levels (% ET_c). Flowering shoots of 13.5% ET_c and 27% ET_c treatments showed

90% inflorescences per node (white circles); however, they did not develop because of water restriction from budbreak to full bloom ($\Psi_{stem} < -2.5$ MPa)

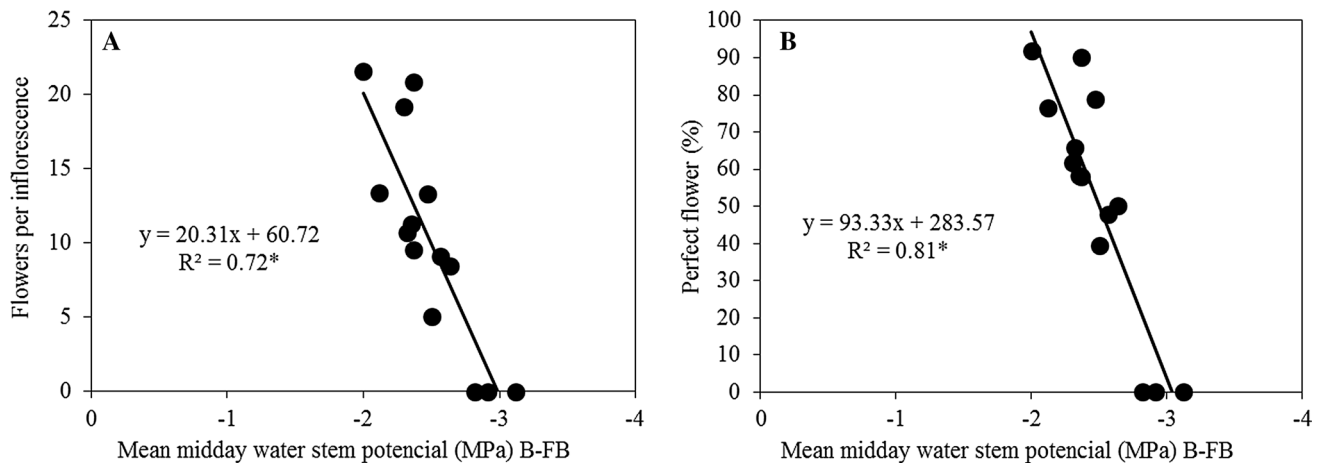


Fig. 6 **a** Flowers and **b** percentage of perfect flowers per inflorescence as a function of average midday stem water potential from budbreak (B) to full bloom (FB), inflorescence development period ($n = 12$). *indicates a significant linear relationship at $p \leq 0.05$

which could be used to control vigor in super intensive orchards (Connor and Gómez-del-Campo 2013).

4 Concluding remarks

Under water stress conditions, both vegetative and productive development of ‘Arbequina’ olive trees were more affected by water status than crop load, from the end of fruit drop to harvest. Nevertheless, the effect of water status was intensified as fruit number increased. In addition, the flower development period was highly sensitive to water stress. During this period, a midday stem water potential threshold above -2.0 MPa should be maintained, to avoid affecting the number of flowers per inflorescence and the percentage of perfect flowers. The results presented here are preliminary, and it is necessary to continue exploring the irrigation thresholds that must be applied in conditions of low water availability without compromising the productive life span of olive orchards and maintaining yield over time.

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