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Plant growth and yield responses in olive (*Olea europaea*) to different irrigation levels in an arid region of Argentina

Guillermo Correa-Tedesco[1], M. Cecilia Rousseaux, Peter S. Searles*

CRILAR-CONICET, Entre Ríos y Mendoza s/n, Anillaco (5301), La Rioja, Argentina

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ABSTRACT

Over the last two decades, a significant increase in intensively managed olive orchards has occurred in the northwest of Argentina where climatic conditions differ greatly from the Mediterranean Basin. Annual amounts of applied irrigation are generally high due to low rainfall, access to deep ground water, and little information about water use by the crop in the region. The objectives of this study were to: (1) assess the responses of plant growth, yield components, and several physiological parameters to five different irrigation levels and (2) determine an optimum crop coefficient (Kc) for the entire growing season considering both fruit yield and vegetative growth. Five irrigation treatments (Kc = 0.50, 0.70, 0.85, 1.0, 1.15) were employed from late winter to the fall over 2 years in a 6-year-old cv. 'Manzanilla fina' olive orchard. Tree canopy volume was approximately 15 m^3 with a leaf area of about 40 m^2 at the beginning of the experiment. During much of each year, the volumetric soil water content was lower in the Kc = 0.50 treatment than in the other irrigation levels evaluated (Kc = 0.85 and 1.15). Although differences in midday stem water potential (Ψ_s) were not always apparent between treatments during the first year, there were lower Ψ_s values in Kc = 0.50 and 0.70 relative to the higher irrigation levels during the second year. Shoot elongation in Kc = 0.50 was about 50% of that in Kc = 1.0 and 1.15 during both years leading to significant differences in the increase of tree canopy volume by the end of the first year. Fruit yield was similar among irrigation levels the first year, but yield reached a maximum value the second year between Kc = 0.70 and 0.85 above which no increase was apparent. The somewhat lower fruit yield values in Kc = 0.50 and 0.70 were associated with decreased fruit number rather than reductions in individual fruit weight. The water productivity on a yield basis (fruit yield per mm of applied irrigation) decreased as irrigation increased in the second year, while similar calculations based on trunk cross-sectional area growth indicated that vegetative growth was proportional to the amount of irrigation. This suggests that the warm climate of northwest Argentina (28° S) can induce excessive vegetative growth when very high irrigation levels are applied. A Kc value of approximately 0.70 over the course of the growing season should be sufficient to maintain both fruit yield and vegetative growth at adequate levels. An evaluation of regulated deficit irrigation strategies for table olives in this region could be beneficial to further reduce irrigation.

1. Introduction

A significant increase in the olive growing area (i.e., 30–90 thousand hectares) has occurred in Argentina over the last 15–20 years similar to other countries in the Southern Hemisphere such as Australia and South Africa. Most of the new commercial plantations are drip irrigated, intensively managed, and relatively large (100–1500 ha). Currently, Argentina is the greatest producer of table olives among these emerging countries, and has become the third-leading exporter globally behind Spain and Egypt with 90,000 tons of table olives exported in 2008 (SAGPyA, 2008; IOOC, 2009).

The new production areas are located primarily in the northwest of Argentina where the climate is substantially different from the Mediterranean Basin (Rana and Katerji, 2000; Ayerza and Sibbett, 2001). Most of the annual precipitation (i.e., 100–400 mm) occurs during the summer months in contrast to the winter rainfall of the Mediterranean, and there are higher temperatures for much of the year due to the subtropical latitude (28–30° S) of the region. These environmental differences may affect the timing of phenological events such as flowering, vegetative growth patterns, oil quality, and yield potential (Ayerza and Coates, 2004; Ravetti et al., 2002; Rondanini et al., 2007). Although olive production relies heavily on irrigation in this region, irrigation requirements and strategies have

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* Corresponding author. Tel.: +54 3827 494 251; fax: +54 3827 494 231.
E-mail addresses: psearles@crilar-conicet.com.ar, psearles2@gmail.com (P.S. Searles).

[1] Present address: Facultad de Agronomía, Universidad de Buenos Aires, Ave. San Martin 4453 (1417), Buenos Aires, Argentina.

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just started to be assessed in high-input orchards (Rousseaux et al., 2008, 2009). Similar initial evaluations have been conducted in the new growing regions of Australia and New Zealand (Yunusa et al., 2008; Greven et al., 2009).

Olive is a drought tolerant species, and many studies have investigated its physiological and morphological adaptations to water stress along with responses of crop yield to deficit irrigation (e.g., Fernández et al., 1997; Moriana et al., 2002; or see review by Connor and Fereres, 2005). Olive water consumption is frequently estimated using the FAO method (Allen et al., 1998) where a crop coefficient (Kc) that represents the ratio of crop evapotranspiration (ETc) to reference evapotranspiration (ETo) is adjusted by the crop cover (Kr) (Fereres and Castel, 1981). The two principal approaches employed for determining Kc values include: (1) estimating a yearly Kc value by measuring the response of tree growth and yield to different yearly irrigation doses or (2) obtaining Kc values for shorter time intervals using agrometeorological techniques such as eddy covariance or physiological measurements (i.e., sap flow or foliar conductance to estimate transpiration) in combination with soil evaporation determinations. Goldhamer et al. (1993) estimated a yearly Kc value of 0.75 for obtaining maximum fruit yields in mature 'Manzanillo' olive trees in California (USA) when analyzing yield response to eight irrigation levels (Kc = 0.16–0.85), while other authors have found similar optimum yearly values of Kc from 0.6 to 0.8 in the Mediterranean Basin (Girona et al., 2002; Moriana et al., 2003). Moriana et al. (2003) described a non-linear yield response to irrigation with both fruit and oil yield increasing dramatically at low irrigation doses, but then reaching saturation with higher irrigation levels. Additionally, Girona et al. (2002) indicated that Kc values of 0.85 and greater may lead to yield reductions due to anoxia in fine textured-soils.

An example of the second Kc approach is that of Testi et al. (2004) where eddy covariance was used to determine daily evapotranspiration over 3 years in a young 'Arbequina' orchard in Córdoba, Spain. From this data set, daily Kc values were calculated for dry soil surface 'summer' conditions, and a linear model was proposed with Kc increasing from 0.15 to 0.30 as crop ground cover increased from 5% the first year to 25% the third year. Wet spots from drip irrigation further increased the Kc values. This second Kc approach estimates water use more directly than applying different irrigation doses and also allows for the determination of monthly Kc values for orchard managers (Rousseaux et al., 2009), but does not provide an integrated evaluation of plant responses to irrigation.

Plant growth including shoot elongation, trunk expansion, canopy volume and pruned biomass can be strongly influenced by irrigation levels (e.g., d'Andria et al., 2004; Gómez-del-Campo et al., 2008; Iniesta et al., 2009). Shoot growth at the end of the season in a super high density orchard (1700 trees ha^{-1}) in California was 75% less in trees receiving 30% of ETc relative to those irrigated with a seasonal amount near 100% of ETc demand (Grattan et al., 2006). Additionally, it appeared trunk growth did not reach maximum levels even under the highest irrigation level (ETc = 140%). In the Mediterranean Basin, it has been suggested that the intensification of management in modern olive orchards may lead to excessive plant growth that could be controlled by decreasing irrigation levels with little or no reduction in yield (Lavee et al., 2007; Pastor et al., 2007), and that maximum vegetative growth may occur at higher irrigation levels than maximum yield (Girona et al., 2002).

Similarly to the Mediterranean Basin, intensively managed olive orchards in new growing regions are characterized by moderate to high use of irrigation water and other inputs, which may result in competition between the agricultural sector and urban population centers (Fereres and Evans, 2006). In the Arid Chaco of Argentina, irrigation levels are often high (i.e., Kc = 0.50–1.0), partly as a consequence of the low energy cost of water extraction from the belowground aquifer (Rousseaux et al., 2008). Thus, irrigation strategies such as continuous or regulated deficit irrigation that are based on the drought tolerant characteristics of olive are currently not considered to be of primary importance (Connor, 2005). In order to improve the water use and yield of olive orchards over the long-term in arid northwest Argentina, the objectives of the present study were to: (1) assess the responses of plant growth, yield components, and several physiological parameters to five different irrigation levels and (2) determine an optimum Kc for the entire growing season considering both fruit yield and vegetative growth.

2. Materials and methods

2.1. Experimental site and irrigation treatments

The experiment was conducted for two growing seasons from September 6, 2005 to May 22, 2007 in a commercial olive orchard located 15 km east of Aimogasta (28°33′S, 66°49′W; 800 m above sea level) in the province of La Rioja in northwest Argentina. The trees (var. 'Manzanilla fina') were 6-year old at the start of the experiment with a canopy volume of approximately 15 m^3, and a lightly pruned, vase conduction system resulting in a leaf area of about 40 m^2. Tree spacing was 4 m between trees and 8 m between rows (i.e., 312 tree ha^{-1}) with a North-South row orientation. The soil was loamy sand in texture with 13% gravel content and a depth of about 1.5 m. The volumetric soil water content at field capacity and wilting point were estimated to be 0.20 and 0.09 $\text{cm}^3\,\text{cm}^{-3}$, respectively. Irrigation was supplied by eight drip emitters per tree using two drip lines. The drip lines were spaced 1 m apart (i.e., 0.50 m on each side of the trunk), and the emitters were installed continuously at distances of 0.95–1.10 m depending on the irrigation treatment. The emitters had a discharge rate of 2 or 4 $\text{l}\,\text{h}^{-1}$, or a combination of both to meet irrigation requirements. Irrigation frequency was two or three times per week.

In order to calculate irrigations levels, the standard FAO formula for crop evapotranspiration (ETc = ETo × Kc × Kr) was used where ETo is the Penman–Monteith reference evapotranspiration over grass, Kc is the crop coefficient, and Kr is the coefficient of reduction associated with percentage crop cover (Fereres and Castel, 1981). The five irrigation treatments (Kc = 0.50, 0.70, 0.85, 1.0, 1.15) employed over the 2 years (i.e., September 2005–May 2006 and September 2006–May 2007) were based on the wide range used by the local growers and allowed an assessment of plant responses to irrigation levels potentially below and above optimum. Reference evapotranspiration (ETo) was calculated from meteorological data obtained from an automatic weather station (Davis Instruments, CA, USA) located in a large, cleared area with bare soil within the commercial orchard. Values of ET over bare soil were adjusted to reference conditions over grass using Annex 6 of Allen et al. (1998). The overall values for Kr were 0.43 in August 2005, 0.52 in June 2006, and 0.56 in January 2007 with no significant differences being apparent between treatments. All experimental plots were irrigated during the winter (i.e., June–August 2006) with a Kc = 0.40 because rainfall is rare in this region during these months. This irrigation level was considered appropriate for meeting the water requirements of the crop during the winter (Rousseaux et al., 2008).

The experimental design was a randomized complete block design with four replicates. Each block contained one plot of each treatment for a total of 20 plots (4 blocks × 5 irrigation treatments). A plot consisted of six consecutive trees within the same row, and measurements were performed on the four central trees. Although border rows were not utilized, the potential for water movement between rows was minimal due to the 8 m distance between rows, and few (if any) roots were apparent at distances greater than 2 m from the drip line (Searles et al., 2009). All experimental plots received the same annual, supplemental fertilizer amounts either added through the irrigation system or as solid below the drip emitters. Supplemental annual amounts per hectare were 64.5 kg N, 9 kg P, 13.5 kg K, 11 kg S, and 20.7 kg Mg. Although nutrient concentrations contained in the irrigation water itself were not considered and were significant for some nutrients (e.g., 5.1 mg l^{-1} K; 13.4 mg l^{-1} Mg), no differences in foliar nutrient concentrations between treatments were detected during the study (data not shown). The plots were weeded monthly, and the trees were not pruned during the 2 years.

2.2. Soil and plant measurements

The soil water content was measured between drip emitters to a depth of 1 m at 25 cm intervals using a soil auger in the Kc = 0.50, 0.85, and 1.15 treatments. Approximately 95% of root length density was found in the upper meter. One sample was taken every 40–60 days (six times per year) from each plot from August to June in the three treatments evaluated. The sub-samples from each depth were weighed in the laboratory and then oven-dried at 90 °C until constant dry weight was reached. Soil bulk density was estimated to be 1.2 g cm^{-3} using a beveled-cylinder to convert gravimetric soil water content to volumetric units. Six capacitance probes (ECH_2O, Decagon Devices, USA) connected to a data logger (Cavadevices, Buenos Aires, Argentina) were installed in one experimental block at a soil depth of 30 cm to provide a secondary estimation of soil water content, and to verify irrigation duration (data not shown).

Midday stem water potential (Ψ_s) under clear sky conditions and predawn leaf water potential (Ψ_{pd}) were measured in all five irrigation treatments with a pressure chamber (Biocontrol, model 0–8 MPa, Buenos Aires). All measurements of Ψ_s and Ψ_{pd} were performed on two short terminal stems per plot, and each stem had two fully expanded leaf pairs. The stems for the Ψ_s measurements were sampled from the shaded interior of the tree canopy near the main trunk 1 h after being enclosed in reflective plastic envelopes to reduce leaf transpiration (Fulton et al., 2001). The water potential measurements were conducted every 40–60 days from September to May in 2006–2007, and slightly less frequently during the first year (2005–2006).

Net photosynthesis and transpiration were measured three times per year around midday over about 3.5 h (11–14.5 solar time) on two leaves per plot in the Kc = 0.50, 0.85, and 1.15 treatments using a semi-portable gas exchange system in open mode (CID Inc., CI-310, Vancouver, WA, USA). Leaf conductance was then calculated. Air flow was 0.4 l min^{-1}, and air temperature in the leaf chamber was within 3 °C of ambient temperature using Peltier cooling. All measurements were made on fully expanded leaves on sunny days. Comparisons of gas exchange values were only made between treatments for a given date and not between dates due to the low number of measurement dates.

Plant growth was assessed for all of the irrigation treatments by determining shoot elongation and increases in both trunk cross-sectional area and tree canopy volume. Shoot elongation was measured every 40–60 days from the beginning of spring to mid-fall on 12 marked, 1-year old reproductive branches per plot and on 12 current year, vegetative branches per plot. Although the reproductive branches had fruit load for much of this period, shoot elongation still occurred over the course of the growing season. The marked branches included all four cardinal directions for three trees per plot, and new branches were marked in each of the 2 years. Tree circumference was measured every 40–60 days similar to shoot elongation at a height of 0.30 m from the soil surface using a flexible tape measure in order to calculate the increase in trunk cross-sectional trunk area. Tree height and canopy width were measured four times over the course of the study to determine canopy volumes. Both the tree circumference and canopy volume parameters were measured on all four central trees per plot.

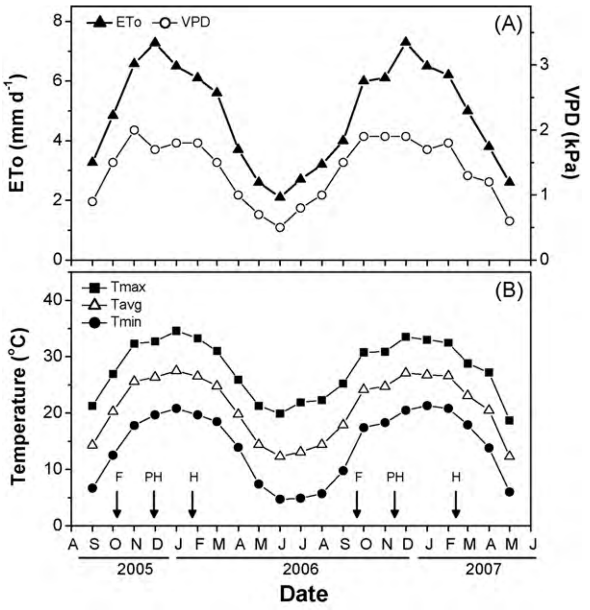

Fig. 1. Average daily values for each month during the experiment (September 2005–May 2007) of reference evapotranspiration (ETo) and vapor pressure deficit (VPD) (A) and of maximum (T_{max}), minimum (T_{min}) and average (T_{avg}) temperature (B). The dates of flowering (F), pit hardening (PH) and harvest of green table olives (H) are indicated with arrows for each year in (B).

Reproductive measurements included the number of inflorescences (two weeks before full flowering) and number of fruits (60 days after flowering) on the marked, reproductive branches mentioned above. Additionally, final fresh and dry fruit weights were determined for 50 fruits per plot shortly before harvest as well as longitudinal and equatorial fruit diameters for 25 fruits per plot. Each plot was harvested in late January or early February to coincide with commercial harvesting for green table olives.

2.3. Statistical analysis

Variables measured over the course of the growing season such as shoot elongation and volumetric soil water content were analyzed with the PROC MIXED procedure of SAS (SAS Institute, Cary, NC, USA) for repeated measures ANOVA following the variance–covariance structure recommendations of Littell et al. (1998). Mean comparisons among treatments for these variables were contrasted using the ESTIMATE function of PROC MIXED. Fruit set, yield, and gas exchange variables were analyzed using the ANOVA procedure of INFOSTAT (University of Córdoba, Córdoba, Argentina), and Tukey's tests were employed to evaluate differences between means.

3. Results

3.1. Meteorological data and applied irrigation

The annual reference evapotranspiration (ETo) averaged 1605 mm for the 3 years from 2005 to 2007. During the study, monthly ETo values ranged from 2.1 during the winter (June 2006) to 7.3 mm d^{-1} during the summer (Fig. 1A; December 2005 and 2006) with a pronounced increase at the beginning of spring during September and October due to rising air temperatures and wind speed (average of 3.5–4.0 m s^{-1}, data not shown). Average daily values of minimum air temperature were 4.7 °C in June 2006 and

Table 1
Total water applied (mm) for each crop coefficient during the spring (September–November), summer (December–February), fall (March–May), and the entire growing season (September–May) for 2005–2006 and 2006–2007. Effective precipitation was only 17 and 12 mm in the first and second growing seasons, respectively.

Crop coefficient (Kc)	Total water applied (mm)							
	September–November		December–February		March–May		September–May (total)	
	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007
0.50	93	125	142	178	98	97	334	400
0.70	128	172	197	243	135	133	460	548
0.85	160	214	241	301	169	166	570	681
1.0	177	229	284	336	193	200	654	765
1.15	212	273	335	399	230	239	777	910

reached a maximum of 34.6 °C in mid-summer (Fig. 1B; January 2006). Average maximum temperatures were greater than 30 °C for approximately five months per year (i.e., mid-spring through late summer). Accumulated precipitation from early spring (September) to late-fall (May) was 73 and 46 mm for the 2005–2006 and 2006–2007 experimental seasons, respectively. Most of this precipitation fell in late-spring or early summer (December and January; data not shown).

The irrigation applied from early spring to late-fall along with a very small amount of effective precipitation (17 mm in 2005–2006 and 12 mm in 2006–2007) was summed to determine total water applied during the growing season. These values ranged from 334 to 777 mm the first year and 400–910 mm the second year, depending on the treatment (Table 1). The low levels of effective precipitation occurred because many of the rainfall events were less than 5 mm, and because a large proportion of the rainfall fell in the inter-row spaces outside of the root zone in this young orchard. The greater amount of water applied in 2006–2007 reflected the increase in canopy cover over the course of the experiment. The water applied was similar from March to May in both years because of inter-annual differences in ETo and a slight over-irrigation in May 2006. All treatments received 43 mm during the winter months (June–August) of 2006.

3.2. Soil water content and stem water potential

Volumetric soil water content at a depth of 0–50 cm was lower in the Kc = 0.50 treatment than in the Kc = 0.85 and 1.15 treatments during most of each growing season (Fig. 2A and B; $P < 0.05$). At the 50–100 cm soil depth, no statistically significant differences between Kc = 0.50 and the other irrigation levels were apparent until February 2006 (mid-summer) during the 2005–2006 season (Fig. 2C). In contrast, soil water content was lower at this depth in the Kc = 0.50 treatment as early as late-October (mid-spring) during the second season (Fig. 2D) possibly due to greater spring ETo values the second season and a slightly earlier start to the experimental treatments. Alternatively, the greater amount of winter irrigation before the start of the experiment by the grower/cooperator in 2005 compared to 2006 may have led to a delayed response to the Kc = 0.50 treatment for soil moisture at the 50–100 cm depth. Apparent differences in soil water content between treatments at the 50–100 cm depth in October 2005 are likely to be merely

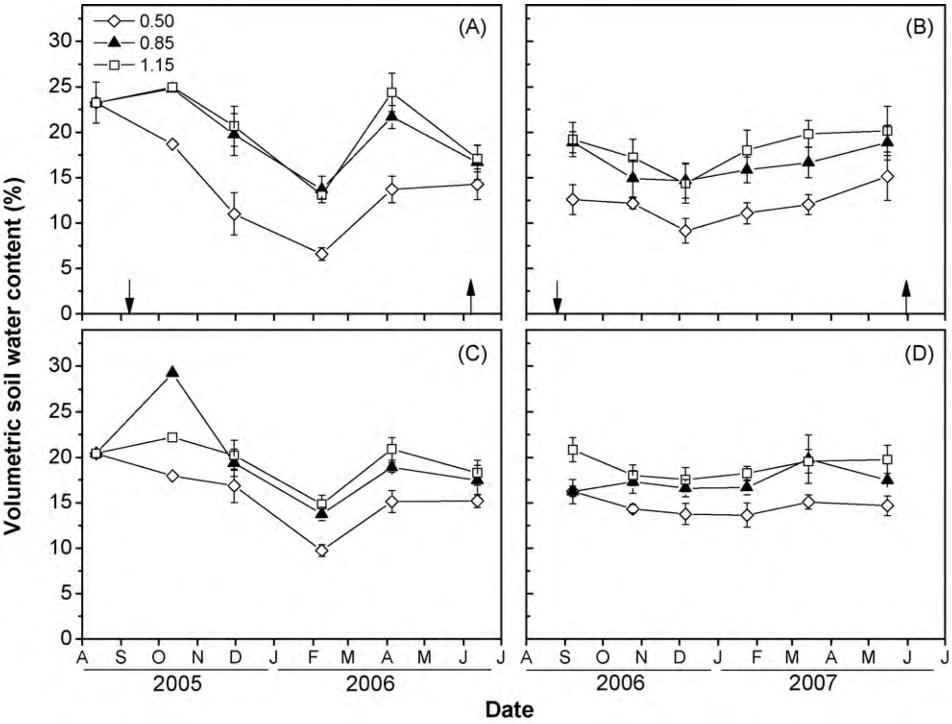

Fig. 2. Volumetric soil water content (%) at a depth of 0–50 cm (A and B) and 50–100 cm (C and D) for the three crop coefficients evaluated (Kc = 0.50, 0.85, 1.15) during 2005–2006 and 2006–2007. Arrows indicate the start and end of the treatments during both years. Means are shown ± standard error ($n = 4$) except for October 2005 when repetitions were not performed. Soil water content at field capacity and wilting point were estimated to be approximately 20% and 9%, respectively.

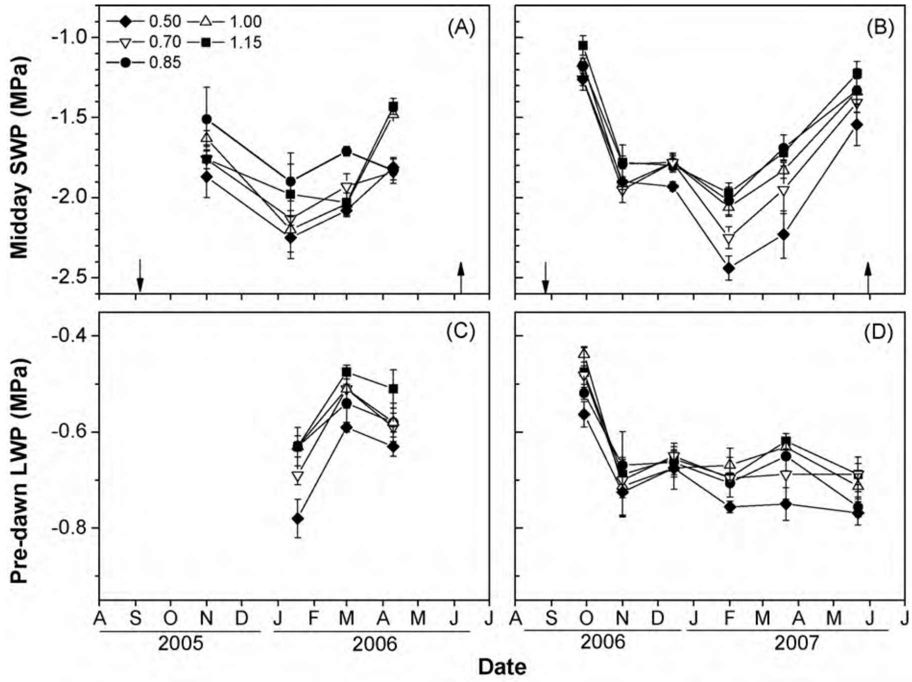

Fig. 3. Midday stem water potential (SWP) (A and B) and predawn leaf water potential (LWP) (C and D) for all five crop coefficients during 2005–2006 and 2006–2007. Arrows indicate the start and end of the treatments during both years. The means are shown ± standard error ($n = 4$).

a reflection of only one soil sample per treatment ($n = 1$) being taken on this date rather than four samples per treatment ($n = 4$) as was the case for the other measurement dates. There were no differences in soil water content between the Kc = 0.85 and 1.15 treatments during the course of the study in the top meter of soil. This may have been related to the soil water holding capacity. No soil samples were taken below a depth of 1 m, nor were multiple sampling positions measured to determine overall wet-bulb size. Irrigation was sufficient at the end of the first season to restore soil water content to a similar level for both the 0–50 and 50–100 cm soil depths in the three treatments evaluated (Fig. 2A and C).

Midday stem water potential (Ψ_s) had a tendency to be lower in Kc = 0.50 than in the other treatments in 2005–2006 using repeated measures ANOVA (Fig. 3A; $P = 0.09$). A more significant difference in Ψ_s occurred between the Kc = 0.50, 0.70, and 0.85 treatments compared to those of Kc = 1.0 and 1.15 towards the end of the first year (April 2006; $P < 0.05$). In the second year (2006–2007), lower Ψ_s values in Kc = 0.50 and 0.70 versus the higher irrigation levels were apparent during both the summer and fall with a minimum value of −2.45 MPa in Kc = 0.50 (Fig. 3B). Similar to Ψ_s, predawn leaf water potential (Ψ_{pd}) values in Kc = 0.50 were lower than in the other treatments during both years (Fig. 3C and D; $P < 0.01$). A significant correlation was found between Ψ_s and Ψ_{pd} over the course of the experiment ($r = 0.70$, $P < 0.01$; data not shown).

3.3. Leaf gas exchange

There was a tendency for leaf conductance (g_l) to decrease with less irrigation throughout most of the experiment (Table 2; $P < 0.10$). Additionally, g_l showed a strong non-linear relationship with stem water potential (Ψ_s) in 2006–2007, where g_l increased markedly with values of Ψ_s above −2.0 MPa ($r^2 = 0.77$; $g_l = 181\Psi_s{}^2 + 865\Psi_s + 1102$). No statistically significant differences between treatments in net photosynthesis were detected.

3.4. Plant growth

Elongation of non-bearing branches (i.e., without fruits) in Kc = 0.50 was about one-half of elongation in the treatments Kc = 1.0 and Kc = 1.15 during 2005–2006 (Fig. 4A; $P < 0.01$). Elongation for the Kc = 0.70 and 0.85 treatments was intermediate. Similar results were apparent in the second year with the elongation of

Table 2
Net photosynthesis (A) and leaf conductance (g_l) of the irrigation treatments with crop coefficients (Kc) of 0.50, 0.85, and 1.15 in 2005–2006 and 2006–2007. The values are means ± standard error ($n = 4$).

Date	Kc	A (μmol m^{-2} s^{-1})		g_l (mmol m^{-2} s^{-1})	
		2005–2006	2006–2007	2005–2006	2006–2007
November	0.50	16.9 ± 1.3	11.6 ± 2.1	86 ± 10*	94 ± 27
	0.85	14.1 ± 2.3	15.4 ± 2.1	77 ± 5*	116 ± 20
	1.15	14.7 ± 2.5	14.5 ± 2.5	114 ± 15*	139 ± 9
February	0.50	12.3 ± 2.5	9.0 ± 1.9	86 ± 11*	70 ± 32*
	0.85	15.3 ± 3.0	11.1 ± 0.8	122 ± 19*	98 ± 32*
	1.15	17.1 ± 2.3	12.2 ± 0.8	149 ± 23*	117 ± 20*
March/April	0.50	9.2 ± 2.6	9.6 ± 3.9	80 ± 12*	72 ± 23*
	0.85	14.0 ± 1.6	12.6 ± 2.3	116 ± 20*	140 ± 33*
	1.15	13.0 ± 3.2	13.9 ± 1.7	140 ± 30*	185 ± 33*

* $P < 0.10$.

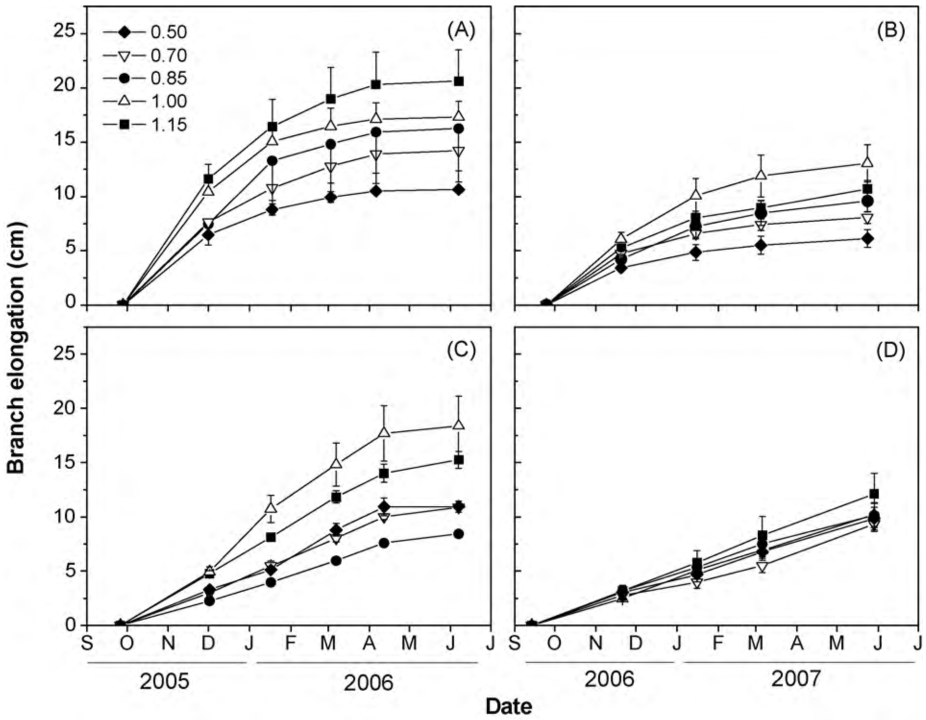

Fig. 4. Elongation of non-bearing (A and B) and fruit-bearing branches (C and D) for all five crop coefficients during 2005–2006 and 2006–2007. The means are shown ± standard error ($n = 4$).

non-bearing branches increasing as irrigation increased (Fig. 4B; $P < 0.01$), although elongation was less overall in 2006–2007 than in 2005–2006. In fruit-bearing branches, elongation in Kc = 1.0 and 1.15 was also much greater than in Kc = 0.50 during 2005–2006 (Fig. 4C). No significant differences among treatments in the elongation of fruit-bearing branches were apparent in 2006–2007 possibly because of higher fruit load during the second season (Fig. 4D).

The increase in canopy volume was 30–60% greater in Kc = 1.0 and 1.15 than the other treatments at the end of the first season (June 2006), and this difference persisted throughout the second year (Fig. 5A; $P < 0.01$). Additionally, trunk cross-sectional area (TCSA) growth showed significant differences among irrigation treatments by late summer of the first year (March 2006) (Fig. 5B; $P < 0.01$). The treatment Kc = 1.15 accumulated approximately 60% more TCSA than Kc = 0.50 and 8% more than Kc = 1.0 over the 2 years.

3.5. Yield components

There were not pronounced differences in fresh fruit yield among treatments during the first year with an average of 18.4 kg tree^{-1} (Fig. 6A; $P = 0.08$) although fruit number was somewhat greater in Kc = 1.15 than in the Kc = 0.85 and 1.0 treatments (Fig. 6B; $P < 0.05$). In the second year, yield reached a maximum between the irrigation levels of Kc = 0.70 and 0.85 above which yield did not increase. Yield was 27% lower in Kc = 0.50 primarily due to a reduction in fruit number (Fig. 6B; $P < 0.01$). No differences among the treatments at harvest were found for fruit diameter or fresh and dry fruit weight in either year (Table 3). Fruit set (i.e., percentage of inflorescences with at least one fruit) and density (i.e., fruit per decimeter of shoot) also were not affected.

3.6. Water productivity

The water productivity on a yield basis (WP$_y$) (i.e., fresh fruit yield per mm of applied irrigation) decreased as applied water increased in 2006–2007 with a maximum value of 21.9 kg mm^{-1} ha^{-1} in the Kc = 0.50 treatment and a minimum of 14.1 in Kc = 1.15 (Fig. 7; $P < 0.01$). This indicates that water use was less efficient as water applied increased. In contrast, the water productivity based on vegetative growth (WP$_{vg}$) (i.e., increase in trunk

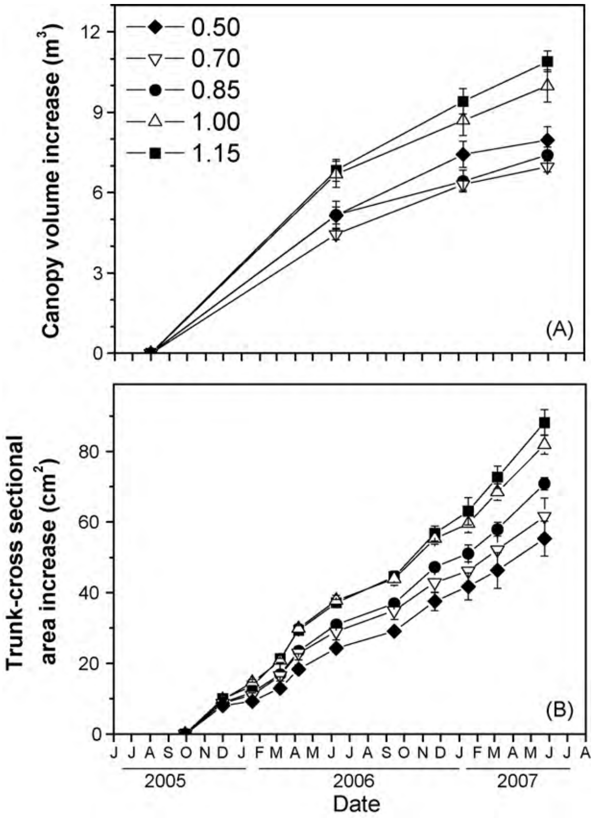

Fig. 5. Increase in canopy volume (A) and in trunk cross-sectional area (B) for all five crop coefficients during 2005–2007. The means are shown ± standard error ($n = 4$).

Table 3
Fruit set, density, longitudinal and equatorial diameter, and fresh weight for 2005–2006 and 2006–2007. The values are means ± standard error ($n = 4$).

Crop coefficient (Kc)	Fruit set (%)		Fruit density (#dm^{-1})		Longitudinal diameter (mm)		Equatorial diameter (mm)		Fresh fruit weight (g)	
	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007
0.50	8.5 ± 3.4	15.0 ± 2.5	0.5 ± 0.2	1.0 ± 0.2	21.8 ± 0.2	23.3 ± 0.4	18.2 ± 0.3	19.1 ± 0.5	4.5 ± 0.2	4.8 ± 0.3
0.70	13.0 ± 3.4	16.0 ± 0.7	1.0 ± 0.3	1.1 ± 0.1	22.3 ± 0.2	23.5 ± 0.1	18.5 ± 0.2	19.2 ± 0.2	4.7 ± 0.1	5.0 ± 0.1
0.85	10.3 ± 1.1	16.7 ± 3.1	0.9 ± 0.1	1.2 ± 0.2	22.4 ± 0.2	23.3 ± 0.1	18.4 ± 0.2	18.8 ± 0.1	4.7 ± 0.1	4.8 ± 0.1
1.00	5.9 ± 0.8	13.8 ± 1.0	0.5 ± 0.1	1.0 ± 0.1	22.3 ± 0.2	23.4 ± 0.1	18.3 ± 0.2	18.8 ± 0.3	4.7 ± 0.1	5.1 ± 0.9
1.15	10.1 ± 0.3	16.6 ± 2.2	0.9 ± 0.1	1.2 ± 0.2	21.9 ± 0.3	23.4 ± 0.4	18.0 ± 0.3	19.1 ± 0.2	4.3 ± 0.2	5.0 ± 0.1

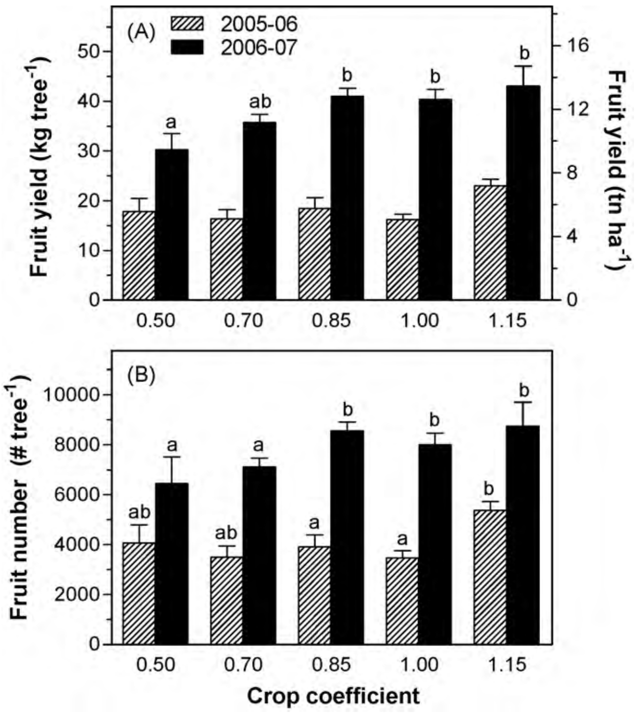

Fig. 6. Fresh fruit yield (A) and estimated fruit number (B) for all five crop coefficients in 2005–2006 and 2006–2007. Means are shown ± standard error ($n = 4$). Different letters represent significant differences among treatments within a given growing season.

cross-sectional area per mm of applied irrigation) in 2006–2007 was relatively high for the Kc = 0.50 treatment, but constant for Kc = 0.70–1.15 ($P < 0.01$). This result for water productivity using trunk diameter indicates that trunk diameter growth was fairly proportional to irrigation applied. Similar results for WP$_y$ and WP$_{vg}$ were found during the 2005–2006 season (data not shown).

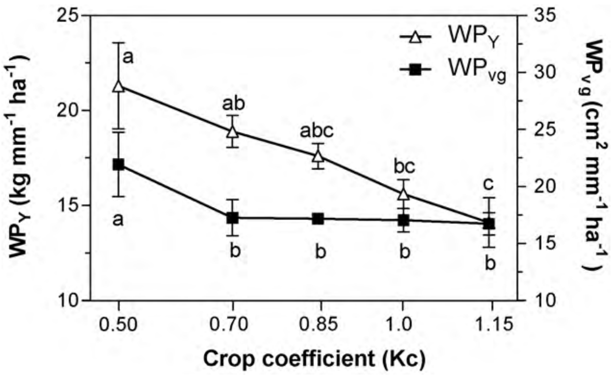

Fig. 7. Water productivity on a fresh fruit yield basis per unit of irrigation water applied (WP$_y$) and water productivity based on vegetative growth (WP$_{vg}$) (i.e., increase in trunk cross-sectional area per mm of water applied) in 2006–2007. The means are shown ± standard error ($n = 4$). Different letters represent significant differences among treatments.

4. Discussion

Reference evapotranspiration (ETo) in the commercial orchard where our study was conducted in arid, subtropical Argentina (28° S) was greater from 2005 to 2007 than occurs on average in most parts of the Mediterranean Basin and California (1600 mm vs. 1200–1400 mm) (e.g., Beede and Goldhamer, 2005; Villalobos et al., 2006; FAO, 2009). In contrast, rainfall was extremely low (<100 mm per year). Although definitive long-term meteorological records are not available, this combination of high ETo and low rainfall will most likely result in large amounts of irrigation water being required in mature orchards in much of northwest Argentina even for moderate Kc values.

As would be expected, the soil water content of the lowest irrigation level (Kc = 0.50) decreased during the spring of each year; especially at the 0–50 cm depth where most of the roots were located (Searles et al., 2009), compared to the much higher irrigation levels (Kc = 0.85, 1.15). Differences in midday stem water potential (Ψ_s) were not always apparent between treatments during the first year, but there were clearly lower Ψ_s values in Kc = 0.50 and 0.70 relative to the higher irrigation levels during the second year. Goldhamer et al. (1994) reported few differences in leaf water potential above Kc = 0.4 in cv. 'Manzanillo' olive trees in California, while Selles et al. (2006) found a tendency for Ψ_s to be lower in Kc = 0.4 versus Kc = 0.7 after 2–3 years of treatment in cv. 'Sevillana' in Mediterranean Chile. A minimum Ψ_s value of −2.4 MPa was measured during the study in the Kc = 0.50 treatment similar to values reported in young 'Arbequina' trees in California (Grattan et al., 2006) and in mature cv. 'Picual' trees in southern Spain (Moriana et al., 2003) for approximately the same Kc. It is likely that a relatively high amount of winter irrigation by the grower/cooperator in 2005 before the start of the experiment in combination with the lowest irrigation level being a moderate Kc value (0.50) contributed to difficulties in detecting a clear response of Ψ_s to the Kc treatments in the first year. Available soil water could have been discounted from irrigation applied at the start of the experiment (Iniesta et al., 2009).

Additionally, the tendency for leaf conductance to be lower in the Kc = 0.50 irrigation treatment may have partially maintained Ψ_s values over the two growing seasons. A delay in the onset of water stress by restricting water loss via stomatal control represents a common drought avoidance mechanism in olive (Connor, 2005). Greater senescence and shedding of older leaves in the Kc = 0.50 treatment also reduced leaf area density and subsequently transpiration (Rousseaux et al., 2009).

With the exception of fruit-bearing branches in the second year when fruit load was high, shoot elongation was the variable most affected by irrigation level with elongation for Kc = 0.50 being about 50% of that for Kc = 1.0 and 1.15. Maximum shoot growth rate in 'Manzanillo' in California was also seen to be very plastic with a 60% reduction in Kc = 0.16 relative to Kc = 0.85 (Goldhamer et al., 1993). In a more integrative manner, differences in stem elongation in the present study led to less canopy volume increase per tree by the end of the first year in the treatments Kc = 0.50, 0.70 and 0.85 versus Kc = 1.0 and 1.15. In the Mediterranean Basin, reductions in canopy volume were measured in young olives trees under deficit irrigation compared to a well-watered control (Pérez-López et al., 2007), and such differences are likely to become greater over several years (d'Andria et al., 2004). Furthermore, trunk cross-sectional area (TCSA) growth did not have a clear limit in response to irrigation level as TCSA growth continued to increase with irrigation even up to Kc = 1.15. Grattan et al. (2006) had similar results for young olive trees in California irrigated with 140% of crop ET in the last season of a 2-year study although shoot elongation reached maximum values with less irrigation. In contrast, trunk growth was reduced in Spain when Kc was greater than 0.70 possibly due to anoxic soil conditions (Girona et al., 2002).

The fruit yield in our study with cv. 'Manzanilla fina' reached a maximum in the range of Kc = 0.70–0.85 in the second year. Similar results were found for 'Manzanillo' in California with no increase in yield or crop value above Kc = 0.75 (Goldhamer et al., 1994). Measurements of sap flow and soil evaporation for periods of 7–10 days within the same plots also indicated that a Kc of 0.7–0.8 allows for a proper estimation of crop evapotranspiration during most of the growing season for the arid northwest of Argentina (Rousseaux et al., 2009). The response of yield to irrigation indicates that the reduction in shoot elongation in the lowest irrigation levels during the first year reduced the potential number of fructification sites and final fruit number the next season. In contrast, there were no apparent effects of irrigation on fruit set or individual fruit weight in either year. Several previous studies have found that fruit set and fruit weight are only decreased if the irrigation levels are very low ($Kc < 0.35$) (e.g., Metheney et al., 1994; d'Andria et al., 2004). Nevertheless, an increase in yield for the Kc = 1.0 and 1.15 irrigation levels would be anticipated relative to that of Kc = 0.70–0.85 if the potential number of fruiting sites was the only factor that influenced yield. Possibly, the greater amount of vegetative growth in the Kc = 1.0 and 1.15 treatments and differences in leaf area density resulted in less light penetration into the canopy interior where flowering or fruit set were not measured (review by Jackson, 1980; Connor et al., 2009). Whole-canopy calculations indicate that leaf area density was 25% greater in Kc = 1.15 than in Kc = 0.50 (Rousseaux et al., 2009), and that fruit number per m^3 of canopy volume was 10–15% less in Kc = 1.0 and 1.15 compared to Kc = 0.85.

The water productivity (WP_y; kg of fresh fruit per mm of irrigation per ha) is a parameter used to evaluate the efficiency of different irrigation management strategies (Fereres and Soriano, 2007). The observed values in the present study ranged from 21.3 $kg\,mm^{-1}\,ha^{-1}$ for Kc = 0.50 to 14.1 for Kc = 1.15 in the second year. This indicates that very high irrigation levels, which are common in commercial orchards in northwest Argentina, lower irrigation efficiency. Of course, greater soil evaporation in the highest irrigation levels as measured by Rousseaux et al. (2009) and drainage of irrigation water below the rooting zone likely explains much of this reduction in WP_y. From a physiological perspective, whole-tree transpiration provides another indicator of WP_y (Iniesta et al., 2009). For our experimental plots, little difference in WP_y on a transpiration basis would be apparent based on periodic sap flow measurements. The values of WP_y reported in this study on an applied irrigation basis are within the same range as those of other authors (e.g., Moriana et al., 2003; Wahbi et al., 2005).

The water productivity on a vegetative basis (WP_{vg}; TCSA growth per mm of irrigation per ha) contrasted with WP_y in that the values of WP_{vg} were relatively constant in the range of Kc = 0.70–1.15. This indicates that TCSA growth was proportional to the water applied. The vegetative growth aspect of water productivity is considered important when evaluating biomass crops such as alfalfa and for annuals such as maize or wheat where water deficits can affect the fraction of harvestable biomass (Fereres and Soriano, 2007). However, little information is available concerning the limits of vegetative growth in fruit trees with respect to water supply especially at subtropical latitudes (Faust, 2000).

The results of our study suggest that high, long-term yields of table olives are obtainable in intensively managed orchards in the arid northwest of Argentina assuming continued access to deep ground water (100–400 m depth) and low costs of irrigation water (i.e., 0.03 euros per m^3). A Kc value of approximately 0.70 over the course of the growing season should be sufficient to maintain both fruit yield and vegetative growth at adequate levels. Higher levels of irrigation will most likely lead to excessive vegetative growth due to the warm meteorological conditions in the region. Vigorous growth raises a number of concerns at the management level including difficulties in harvesting large trees, the potential for increased competition for light within and between tree canopies, and the necessity to prune more frequently. An assessment of regulated deficit irrigation strategies for table olives in this region could be beneficial in further reducing water use.

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