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Combined effects of deficit irrigation and crop level on early nectarine trees

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ABSTRACT

A three-year long experiment was implemented in an early nectarine (*Prunus persica* L. Batsch cv. Flanoba) commercial orchard to evaluate the effects of deficit irrigation and different crop levels on vegetative growth, plant water status, and fruit yield and quality. Three irrigation treatments were assessed: (i) control, full irrigation (T_{CTL}); (ii) normal practice of the farmer (T_{FRM}); and (iii) regulated deficit irrigation (T_{RDI}), which involved irrigating the crop at the same level as the control (T_{CTL}) during the critical periods of the first year and at 60% T_{CTL} during postharvest. In the last two growing seasons the irrigation was scheduled to maintain the signal intensity (SI) of maximum daily trunk shrinkage ($SI_{MDS} = MDS_{TRDI}/MDS_{TCTL}$) at different water stress levels depending on the phenological stage: SI = 1.0 (non-water stress) and SI = 1.4 (moderate water stress). Besides, during the last two seasons, the interactions between T_{CTL} and T_{RDI} were studied at five different crop levels, which were obtained by controlling the distance between fruits left on the branches: from very low (16 cm between fruits) to very high (8 cm between fruits). Crop water use efficiency (WUE) of T_{RDI} was higher than in T_{CTL} and T_{FRM}, increasing by around 25% in 2010 and 2011, and around 74% the final year. Interestingly, T_{FRM} increased the WUE from the first year by more than 30%. The yield/annual increase in trunk-cross-sectional area (ΔTCSA) ratio increased in T_{RDI} with respect to the other treatments as the experiment progressed, reaching differences of 53%. Vegetative growth was clearly sensitive to deficit irrigation with a strong correlation between the increase in the water stress integral obtained by midday stem water potential (Ψ_{stem}) and the reduction in TSCA. In contrast, fruit production and quality were not affected by water deficit. As regards the interaction between crop level and water deficit, fruit firmness was the only fruit quality parameter studied that presented significant differences, the highest values corresponding to the fruits from T_{RDI} trees and the lowest crop level. In early nectarine trees, the postharvest period can be considered as a non-critical period for applying RDI strategies but only when the water stress integral applied is of low intensity in May and June (much lower than 9 MPa day), in order to limit the decrease in vegetative growth and so not affect the following harvests.

1. Introduction

Peach and nectarine trees (*Prunus persicae* L. Batsch) are two of the main deciduous fruit species grown in Spain with an average production of 1,175,500 t per year in the period 2010–2012 (FAOTSAT, 2015). Extra-early varieties are mainly characterized by their high export value, being among the first to be marketed due to their attractive colour and taste (Alcobendas et al., 2012). In areas of water scarcity, it is necessary to use irrigation techniques efficiently, not only to save water, but also to increase productivity and obtain good-quality fruits (Fereres and Soriano, 2007).

Generally, growers schedule irrigation according to experience, although they are also conditioned by the volume of water available (low in many areas suffering from water scarcity), the irrigation system installed and the different agricultural techniques of their farms. Thus, while farmers often achieve high efficiencies in water use, they sometimes apply too much water, usually during fruit growth to obtain fruit of maximum size, but also during the postharvest period in early maturing fruit trees. They would therefore benefit from protocols to achieve greater efficiency by optimizing the applied water using soil and plant water status indicators to control irrigation water leaching.

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Deficit irrigation (DI) has traditionally been defined as an irrigation strategy in which the amount of water applied is lower than that needed to fully satisfy the crop water requirements. DI aims to increase water use efficiency (WUE) by eliminating irrigation events that have little impact on yield. However, this application can also have other benefits related with (i) decreasing nitrate leaching, (ii) reducing the energy used during irrigations (since most irrigation equipment is pressurized), and (iii) maximizing the competitiveness of the agricultural sector. Moreover, early studies reported improved fruit quality due to a higher maturity index as result of an increase in the phenolic composition of fruit, especially in the case of extra early varieties with a short ripening time (Buendía et al., 2008; Falagán et al., 2015). In late varieties of nectarine under RDI Thakur and Singh (2013) found a higher concentration of sugars, higher levels of total phenols, and higher antioxidant, ascorbic acid and anthocyanin levels. Differences from the levels obtained in a control treatment increased with the severity of RDI.

One of the most important DI strategies developed in fruit trees is regulated deficit irrigation (RDI, Chalmers et al., 1981), whereby water restrictions are applied in non-critical periods, when fruit growth is less sensitive to soil water deficit, while covering the full water requirements during the rest of the growing season (Buesa et al., 2013; Mitchell et al., 1989). In this sense, Stage II of fruit growth (slow fruit growth rate) and the postharvest period are suitable times for reducing irrigation in extra-early nectarine trees (De la Rosa et al., 2015). Postharvest is the longest non-critical period of the growing season, and is important because it is when carbohydrate reserves accumulate and floral differentiation processes occur (Handley and Johnson, 2000). Therefore, RDI must be managed carefully in order to avoid reductions in bloom and fruit load (Pérez-Pastor et al., 2015). RDI has successfully been studied in a wide range of fruit crops (see reviews of Ruiz-Sánchez et al., 2010 and Pérez-Pastor et al., 2015). In stone fruits (e.g., nectarine), RDI has been used to control vegetative growth, decreasing competition between vegetative and fruit growth (Ruiz-Sánchez et al., 2010). However, a severe water deficit may result in a serious reduction of vegetative growth, reducing the number of fruits per trees (by decreasing the tree size), or even cause disorders in the following harvest (Naor, 2014). To solve this, plant water status needs to be controlled by using indicators when such strategies are applied. Recently, continuous measurements of plant water status through the use of trunk diameter fluctuations (TDF) have been used for irrigation scheduling in real time with high precision, thus reducing the possible dangers of RDI applied during the water deficit periods (Fernández and Cuevas, 2010; Ortuño et al., 2010). Maximum daily shrinkage (MDS), which covers cycles of shrinking and swelling induced by changes in transpiration (Corell et al., 2014) is considered one of the most sensitive water stress indicators (De la Rosa et al., 2014). However, the fact that MDS integrates the effects of weather conditions and the soil water availability promoted the use of MDS signal intensity (SI_{MDS}, Golhamer and Fereres, 2004) as a suitable irrigation scheduling technique (De la Rosa et al., 2015; Puerto et al., 2013).

The response of nectarine yield to water deficit must be considered together with its response to climatic conditions and fruit thinning practices (Naor et al., 2005). In fact, as crop load increases, the seasonal growth of trunk diameter and tree biomass accumulation may be reduced as a result of increased carbohydrate partitioning towards fruit (Berman and DeJong, 1997). However, Intrigliolo et al. (2014) reported that crop load reduction could be employed to alleviate the detrimental effects that long-term RDI strategies have on tree growth.

Early reports assessed the combination of water deficit and crop level in fruit trees (Alcobendas et al., 2012; Intrigliolo et al., 2014; Lopez et al., 2007; Naor et al., 2013). However, to our knowledge, this work represents the first time that the above interaction has been studied using the conceptual approach of SI_{MDS} for irrigation management, while being compared with growers' irrigation practices. For these reasons, a three-year long experiment was implemented in an early nectarine commercial orchard, to evaluate the effects of the deficit irrigation on vegetative growth and crop level using the $SI_{MDS,}$ seeking to maintain the yield and fruit quality standards necessary to increase growers' benefits.

2. Materials and methods

2.1. Experimental site

The study was performed during three consecutive growing seasons (2009–10; 2010–11 and 2011–12) in a commercial orchard located in Murcia (38° 8′ N; 1° 13′ W). Each growing season was taken to begin on the first day of post-harvest and end on the last day of harvest of the following year. The experimental plot had an area of 2 ha of seven-year-old early nectarine trees (*P. persicae* L. Batsch cv Flanoba) grafted onto hybrid GF677 rootstock at a spacing of 5.5 m × 3.5 m. At the beginning of the experiment the trunk diameter of the trees averaged 14.2 cm, without differences between treatments. The soil, with an average depth of 1.55 m, had low available potassium (236 mg kg^{-1}), soluble phosphorus (6.6 mg kg^{-1}) and organic matter (0.8%) contents, a clay loam texture and high levels of chloride and sodium (4.37 and 8.87, respectively, in aqueous extract 1:2). The electrical conductivity (EC) of the irrigation water varied between 1.5 and 2.5 dS m^{-1}, according to the source used (irrigation canal, well or a mix of both), with maximum levels of chloride and sodium of around 12.6 and 13.4 meq L^{-1}, respectively. Usual horticultural practices (eg., weed control, fertilization, pruning, fruit thinning and girdling) were carried out by the technical department of the commercial orchard. The weather was typically Mediterranean, with hot, dry summers and mild, wet winters. Annual average temperatures were 17.9, 17.3 and 17.6 °C for the 2009–10, 2010–11 and 2011–12 seasons, respectively, with the maximum temperature (43.8 °C) occurring in the summer of 2009. Rainfall was mainly distributed between autumn and spring, amounting to 296, 256 and 290 mm, respectively, for the three seasons studied.

A drip irrigation system was installed, with two lines per tree row spaced 1.2 m and 9.33 pressure-compensated emitters (1.6 L h^{-1}) per tree placed every 75 cm.

2.2. Irrigation treatments

During the three consecutive growing seasons of the experiment, three irrigation treatments at commercial crop level, were carried out: (i) Control, T_{CTL}, irrigated at 110% of ETc (maximum crop evapotranspiration) during the whole season in order to avoid limiting soil water conditions; the ETc was determined from the crop reference evapotranspiration (ET_0 Penman–Monteith, Allen et al., 1998); (ii) farmer treatment (T_{FRM}), irrigated according to the farmer's normal practice; this involved applying irrigation water above T_{CTL} levels during the first season, and reducing the irrigation amount as the study progressed as in the case of T_{RDI} (Fig. 1); and (iii) regulated deficit irrigation, T_{RDI}, irrigated for the first season (2009–10) at 110% of ETc during the critical periods (second rapid fruit growth period and two months after harvest) and at 60% of T_{CTL} during late postharvest (from July until the end of the growing season). The irrigation scheduling protocol of this treatment varied each season according to the information obtained from the MDS and midday (12.00 h solar time) stem water potential (Ψ_{stem}) measurements in the previous year. Therefore, during the final two seasons (2010–11 and 2011–12) the irrigation was scheduled to

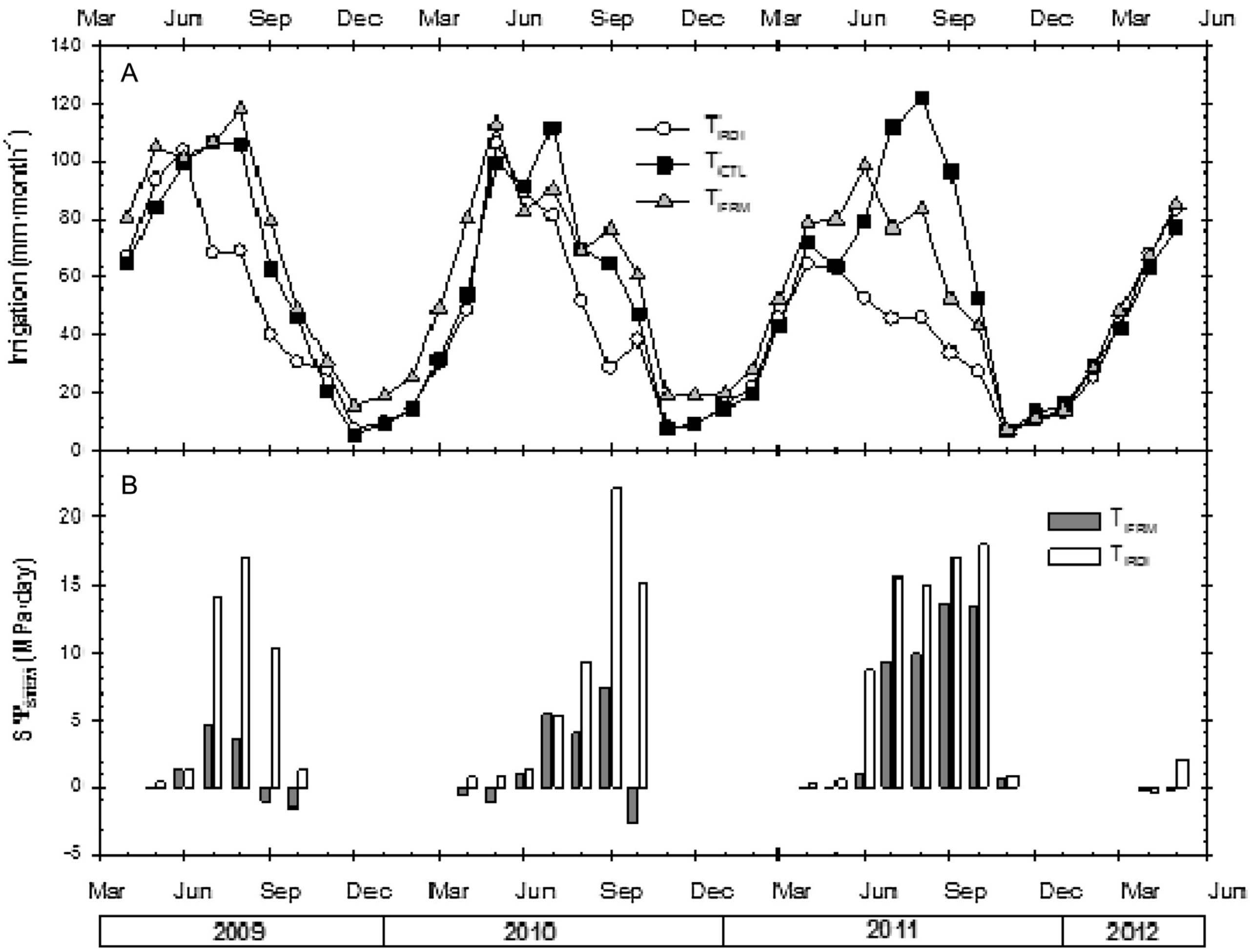

Fig. 1. Monthly values of irrigation (A) for the three irrigation strategies: T_{RDI} (—○—), T_{CTL} (—■—) and T_{FRM} (—△—) and water stress integral values ($S\Psi_{STEM}$, B) for T_{FRM} (▬) and T_{RDI} (▭).

maintain the signal intensity (SI) of the maximum daily shrinkage of the trunk (MDS, $SI_{MDS} = MDS_{TRDI}/MDS_{TCTL}$) depending on the phenological stage at different water stress levels: SI = 1.0 (non-water stress) during the fruit growth and early postharvest (May) and SI = 1.4 (moderate water stress) during late postharvest period (from July until the end of the growing season in 2010–11, and from the end of May until the end of the season in 2011–12) (De la Rosa et al., 2015).

ETc was determined as the product of reference crop evapotranspiration (ET_0), the crop coefficients proposed by the Agricultural Information System of Murcia (www.siam.es) for this area adjusted for the tree size (Fereres and Goldhamer, 1990), and an additional leaching fraction applied due to the saline nature of the irrigation water. The leaching fraction was determined by the method described by Maas and Hoffman (1977), measuring the electrical conductivity of the irrigation water.

Irrigation was scheduled weekly with a frequency that varied from 1 to 2 times per day in spring-summer to 1–7 irrigations per week for the rest of the year. The start time of the irrigation was the same for all treatments, and was during the night (between 3 and 5 a.m.). The number of irrigations was the same in all irrigation treatments and the amounts of irrigation water applied were varied by varying the run time.

The experimental design consisted of 3 replicates per treatment, randomly distributed within the orchard. Each replicate had three adjacent tree rows and 15 trees per row. Measurements were taken from the trees in the central row, with the other trees serving as borders.

2.3. Fruit thinning treatments

The effect of different crop levels on production and quality was evaluated in 2011 and 2012 in T_{CTL} and T_{RDI}. Five different crop levels were achieved by leaving different distances between fruits on the branch: (i) very low (16 cm between fruits); (ii) low (14 cm between fruits); (iii) normal or commercial (12 cm between fruits); (iv) high (10 cm between fruits); and v) very high (8 cm between fruits). In addition, malformed, poorly positioned or very small fruits were eliminated in all treatments. Each type of thinning was performed on three representative trees randomly selected within each treatment. All subsequent measurements (production, number of fruits, fruit size, soluble solids, firmness, acidity and maturity index) were performed individually on each tree.

2.4. Measurements

2.4.1. Weather

An automatic weather station located close to the orchard provided climatic data: air temperature, relative humidity, solar radiation, rainfall and wind speed. The weather station was composed of an anemo vane (Young, model 05103-5, USA), radiometer (Kipp and Zonen, model CMP6, Netherlands), pluviometer (Thies-

Clima, model 5.4031.30.006 Germany), datalogger (Campbell, model CR100) and thermo-hygrometer (Vaisala, model HMp45AC, Finland).

2.4.2. Plant water status

Midday (12.00 h solar time) stem water potential (Ψ_{stem}) was measured every 7–10 days in one leaf per tree on the same trees that were monitored with linear variable displacement transducers (LVDT), enclosing the leaves in foil-covered plastic and aluminum envelopes for at least 2 h before the measurement. Measurements were made using a pressure chamber (Soil Moisture Equipment Corp., Model 3000) according to the procedure described by Hsiao (1990).

The water stress integral was calculated monthly from the midday stem water potential values ($S_{\Psi stem}$, MPa day), as in Myers (1988):

$$S_{\Psi STEM} = \sum_{i=0}^{i=t} \left(\bar{\Psi}_{STEM i,i+1} - \bar{\Psi}_{STEMCTL i,i+1} \right) n \quad (1)$$

where t is the number of measurements of each treatment; $\bar{\Psi}_{STEM i,i+1}$ is the mean Ψ_{stem} values for any interval i, $i+1$; $\bar{\Psi}_{STEMCTL i,i+1}$ is the mean values for T_{CTL} at that interval; and n, the number of days in the interval.

Trunk diameter fluctuation was monitored in six trees per treatment (two trees per replicate), using LVDT sensors (Solartron Metrology, Bognor Regis, UK, model DF ± 2.5 mm, precision ± 10 μm) installed on the northern side of trunks, 30 cm above the ground and mounted on holders built of aluminium and invar (an alloy comprising 64% Fe and 35% Ni, which has minimal thermal expansion). Measurements were taken every 30 s, and 10 min means were recorded by a CR1000 data logger (Campbell Scientific, Inc., Logan, USA), connected to an AM16/32 multiplexer programmed to report mean values every 10 min. Several TDF-derived indices were calculated according to Goldhamer and Fereres (2001): maximum (MXTD) and minimum (MNTD) daily trunk diameter, maximum daily trunk shrinkage (MDS = MXTD – MNTD) and trunk daily growth rate (TGR, calculated as the difference between MXTD of two consecutive days).

2.4.3. Tree and fruit growth

Trunk perimeter was measured every 2–3 months with a tape measure on five trees per replicate at a marked location about 0.3 m from the soil surface. Trunk cross-sectional area was estimated from the circle area. The annual increase in TCSA (ΔTCSA) was calculated as the difference between two TCSA measurements made at the end of harvest in two consecutive years. Pruning dry weight was determined annually during winter dormancy and summer in five trees per replicate. Shoot growth was measured every 1–3 weeks with a tape measure on 20 shoots per replicate selected at the beginning of the experiment.

Fruit diameters (perpendicular to the fruit suture) were measured in 30 randomly selected fruits per replicate every 3–7 days during fruit growth and at harvest time using an electronic digital calliper. Fruit weight before harvest was estimated from the diameter measurements using the equation previously determined (Fw (g) = 0.065 + 0.0029 $Fd^{2.56}$ (mm) r^2 = 0.999). Fruit daily growth rate was calculated as the difference between two consecutive fruit weights divided by the number of days between measurements.

2.4.4. Yield determinations and fruit quality

Mature nectarine fruits were harvested on 4–6 picking dates, starting at the beginning of May each year, with the exact commercial picking dates depending on the year. The total number of fruits on each occasion was weighed and counted from ten trees of each replicate. Average fruit weight was calculated by weighing and counting the fruits per tree. Crop load was determined as the ratio of the number of fruits to TCSA, and crop level as the number of fruits per tree. The yield/TCSA ratio (kg of fruit produced per unit of TCSA) has been defined as yield efficiency (Ebel et al., 1995; González-Altozano and Castel, 1999).

Fruit quality was determined in samples of 20 fruits per replicate from each harvest date. Immediately after harvesting, all samples were transported to the laboratory in about 1 h, where they were analyzed. Total soluble solids (TSS) were determined in fruit juice by using a hand refractometer (Atago N1, Tokyo, Japan). The titratable acidity (TA) of the fruit juice was determined by titrating 5 mL of juice with 0.1 mol L^{-1} NaOH and expressed as a percentage of malic acid. The maturity index was calculated as the TSS TA^{-1}. Flesh firmness was determined on both sides of the fruit with an FT-327 penetrometer (Effeggi, Milan, Italy) with a piston diameter of 7.9 mm (0.5 cm^2), after removing the epidermis of the equatorial zone on both sides of the fruit.

Water use efficiency (WUE) was determined as the ratio between yield and the total amount of water applied (irrigation), yield efficiency ratio as kg of fruit produced per unit of trunk cross-sectional area (kg cm^{-2}) and carbon partitioning between vegetative and productive growth as kg of fruit produced per trunk cross-sectional area increase (kg Δcm^{-2}).

2.4.5. Statistical analysis

Analysis of variance (ANOVA) was used to discriminate the main treatment effects. Means were compared with a Duncan multiple range test at 95% confidence level. All analyses were performed using Statgraphics software (Statgraphics Plus for Windows Version 4.1). Relationships between crop level and production and quality parameters were explored through linear regression analyses. Analysis of covariance was used to determine differences between linear regressions.

3. Results

The average monthly amount of water applied in the three irrigation treatments, together with the water stress integral measured from midday stem water potential ($S_{\Psi stem}$), are presented in Fig. 1. The water applied in T_{CTL} was 681 mm, 617 mm, and 719 mm for the three growing seasons (2009–2010, 2010–2011, and 2011–2012), respectively. The T_{RDI} treatment received 17, 15 and 37% less water than the control in the three seasons, respectively. In contrast, the T_{FRM} treatment had more water applied than T_{CTL} (about 20 and 5%) during the first two years, and 10% less during the third growing season (Fig. 1 and Table 1).

$S_{\Psi stem}$ values increased as the experiment progressed and depended on the reduction in the water applied in T_{RDI} and T_{FRM} with respect to T_{CTL} (Fig. 1). The highest value was reached in the second year in September (around of 23 MPa day). During the final year, the values of $S_{\Psi stem}$ were similar to those of the two previous years but remained high for longer, with values above 9 MPa day per month from June to October, corresponding to less than 60 mm $month^{-1}$ of irrigation water applied, while control trees received more than 100 mm $month^{-1}$.

The trunk growth rate (TGR) of well-watered trees presented two different periods. First, from February to April (around 30 μm d^{-1}), coinciding with the beginning of leaf emergence and then secondly from harvest to August, corresponding to the highest trunk growth rate values of the season (around 60 μm d^{-1}) (Fig. 2B,C). Trees from T_{CTL} presented similar TGR values during each year throughout the experiment. T_{FRM} trees presented the highest values of MXDT in the first year, while in the second year the values were similar to T_{CTL}. TGR particularly decreased during the

Table 1
Amounts of irrigation water applied, water saving relative to control, production parameters (Yield, crop level and fruit weight), vegetative growth (pruning and annual increase in trunk-cross-sectional area-ΔTCSA) and efficiency parameters (water use efficiency-WUE, crop load and yield per ΔTCSA) for the three irrigation strategies (T_{CTL}, T_{RDI} and T_{FRM}) and for each season (2009–2010, 2010–2011 and 2011–2012).

		Irrigation		Production parameters			Vegetative growth		Efficiency parameters		
		Absolute (mm)	Saving (%)	Yield (kg tree^{-1})	Crop level(nºF tree^{-1})	Fruit weight (g)	Pruning(kg tree^{-1})	DTCSA(cm2 y−1)	WUE (kg m^{-3})	Crop load (kg cm^{-2})	Y × DTCSA^{-1} (kg cm^{-2})
2009–10	T_{CTL}	681		38.8	371	105	12.1a	20.4b	3.0a	0.22	1.9a
	T_{RDI}	565	17	40.9	392	104	11.3a	16.4a	3.8b	0.23	2.5b
	T_{FRM}	817	−20	42.2	387	109	15.5b	22.6b	2.7a	0.23	1.9a
	ANOVA	–	–	ns	ns	ns	0.008	0.018	0.006	ns	0.032
2010–11	T_{CTL}	617		53.9	494	109	12.5b	27.1b	4.5a	0.26	2.0a
	T_{RDI}	522	15	56.3	509	111	10.9a	22.8a	5.6b	0.28	2.5 b
	T_{FRM}	654	−6	58	511	113	14.6b	25.7b	4.6a	0.27	2.2 a
	ANOVA	–	–	ns	ns	ns	0.011	0.021	0.025	ns	0.044
2011–12	T_{CTL}	719		43.5	392	111	14.8b	24.1c	3.1 a	0.18a	1.8a
	T_{RDI}	454	37	47.7	433	110	11.5a	17.2a	5.5 b	0.22b	2.8b
	T_{FRM}	648	10	44.4	401	111	14.7b	21.5b	3.6a	0.19a	2.0a
	ANOVA	–	–	ns	ns	ns	0.001	0.002	<0.001	0.037	0.01
Average	T_{CTL}	672		45.4	419	108	13.1b	23.9b	3.5 a	0.22	1.9 a
	T_{RDI}	514	23	48.3	445	109	11.2a	18.8a	4.9b	0.24	2.6b
	T_{FRM}	706	−5	48.2	433	111	14.9b	23.3b	3.5a	0.23	2.1 a
	ANOVA	–	–	ns	ns	ns	0.006	0.011	<0.001	ns	0.008

ns, not significant. Means for each column followed by different letter are significantly different at $P < 0.05$, according to Duncanís multiple range test after irrigation effects were shown to be significant by ANOVA test with $P < 0.05$.

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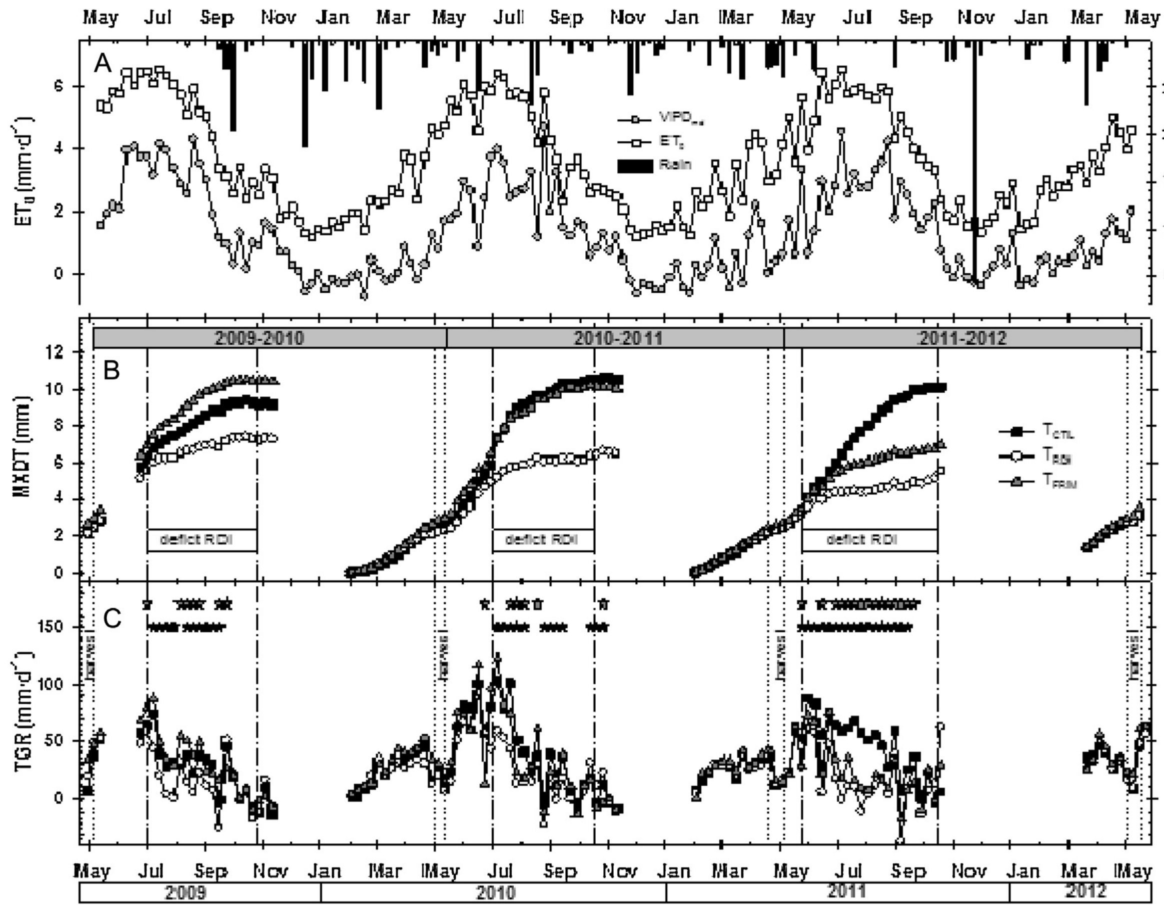

Fig. 2. (A) Seasonal evolution in reference crop of evapotranspiration (ET_0,–□–), midday air vapour pressure deficit (VPD_{md}, –◇–) and rainfall (▬); (B) maximum daily trunk diameter (MXDT) and (C) trunk daily growth rate (TGR) for T_{RDI} (–○–), T_{CTL} (–■–) and T_{FRM} (–△–). Each point corresponds to the daily average of 6 sensors. White (T_{RDI}) and gray (T_{FRM}) stars indicate significant differences from T_{CTL} at $P < 0.05$. Vertical dashed lines and dotted lines mark the water deficit period and harvest periods, respectively.

summer season (by about 53%) compared with T_{CTL} in the last year studied, leading to an overall decrease of 32% in TGR, (Fig. 2B,C). T_{RDI} exhibited a decrease in MXDT values according to the water deficit applied, with a total reduction of around 45% in trunk growth with respect to the control in the three years of the study (Fig. 2B). TGR values decreased gradually with the decrease of soil water content during the mid-summer period, caused by the decrease in applied water (Fig. 1), while in the other treatments it grew by around 50 μm d^{-1}. However, in August/September rainfall led to occasional increases in these values (Fig. 2A,C).

The trunk-cross-sectional area (TCSA) showed the highest values in T_{FRM}, matching control values in the third year. The pattern of TCSA was similar to that of TGR and MXDT explained above. T_{RDI} only presented lower values than the other two treatments after three cycles of deficit irrigation (Fig. 3A). However, the annual increase in trunk-cross-sectional area growth measured at the end of every harvest was significantly lower in T_{RDI} following the first year of deficit irrigation than in T_{CTL} (Table 1). This trend continued until the end of the experimental period, reaching maximum differences of 29% in the third year. In T_{FRM} the values fell with respect to the control, leading to significantly lower values than in the control at the end of the third year (Table 1).

The weight of all the branches removed in summer and autumn pruning during the experimental period in the different irrigation treatments is shown in Fig. 3 and Table 1. During the experiment, pruning weights were slightly higher in summer than in autumn (Fig. 3B). T_{FRM} presented the highest values from the beginning of the study (22% higher than control), although the differences became less pronounced as the experiment progressed. T_{RDI} showed significant differences only in the winter pruning of the third year (23% less than control and farmer) (Fig. 3B). However, the mean values were always lowest in the RDI treatment. The shoot length presented a sigmoid trend during the experimental period, with only one exponential growth period between the beginning of May and mid-June (Fig. 4). The second slope of the curve was due to the harvest. There were no significant effects of the different irrigation strategies on shoot length due to the high variability of the data obtained (Fig. 4).

Fruit diameter growth for the three years of the study (Fig. 5A,B) tended to reflect the three growth stages typical of stone fruits. Despite the early ripening of this cultivar and the continual increase in fruit fresh weight, there was a clear slowing down in the second stage, corresponding to lignification of the endocarp, although this was less evident in the third year. The duration of these stages averaged 25 days from full bloom for stage I, 10 days for stage II and 15–20 days for stage III (Fig. 5). No differences between treatments were detected since there was no water stress level, due to the similar amounts of water received by the trees (Fig. 1).

When the trunk and fruit growth rates were compared, a certain parallelism was observed. While the fruit growth rate was increasing at a rate of 0.1 and 1.5 g per day, the trunk growth rate was maintained at around 40 μm day^{-1}, but interestingly, when FGR reached 4 g per day in the third fruit growth stage, TGR showed minimum values, of around 10 μm day^{-1} (Fig. 6). Later, when the fruits were harvested, the trunk grew faster (TGR ≈ 50 μm day^{-1}).

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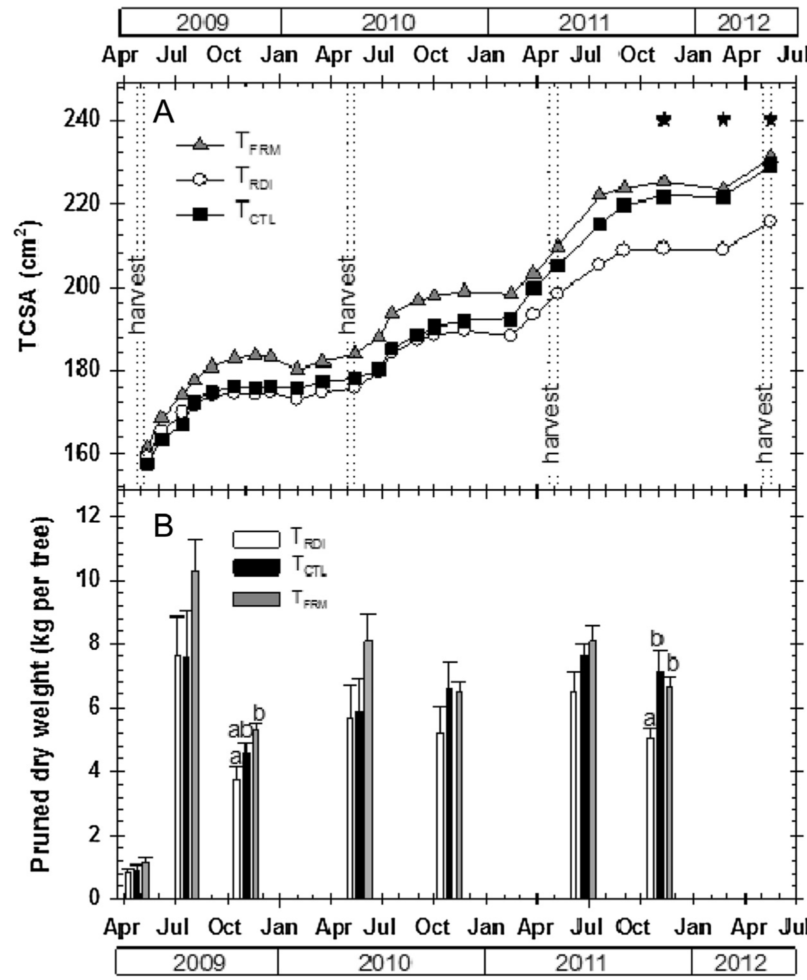

Fig. 3. (A) Seasonal evolution of the mean trunk cross-sectional area (TCSA) during the three growing seasons and (B) pruned dry weight for T_{RDI} (white), T_{CTL} (black) and T_{FRM} (gray). Different letters are significantly different according to Duncanís multiple range test ($P < 0.05$). Each bar and point corresponds to the mean of four replications (five trees per replication) ±SE. Dotted lines delimit the harvest periods.

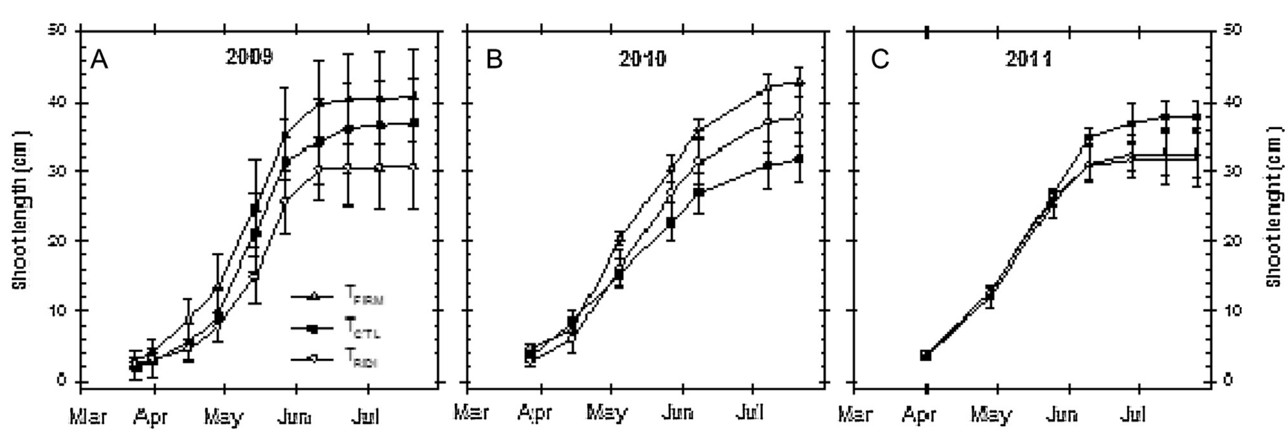

Fig. 4. Seasonal patterns of shoot length during 2009 (A), 2010 (B) and 2011 (C) for T_{RDI} (—○—), T_{CTL} (—■—) and T_{FRM} (—△—). Each point corresponds to the mean of four replications (five trees per replication and two shoot per tree) ±SE.

Harvesting was divided into a different number of picks per year (5, 4 and 6, respectively), starting around the end of April (120 DOY). Total yield in the control treatment, was 38.8, 53.9 and 43.5 kg tree^{-1} for the three seasons. The fruit weight decreased with the date of harvest—from 110 g per fruit (first pick) to less than 100 g (last pick) (Fig. 7). The yield was higher in the second year, due to the higher number of fruit per tree, because of a less fruit thinning and consequently yield increased 28% (Table 1). The average of number of fruit per tree ranged between 383 and 408, in the first and the third year, and 504 fruit per tree in the second year. The main fruit sizes for each of the treatments corresponded to class B (around 55%) and C (around 30%), and only a 10% for size A, with no differences between treatments (data not shown).

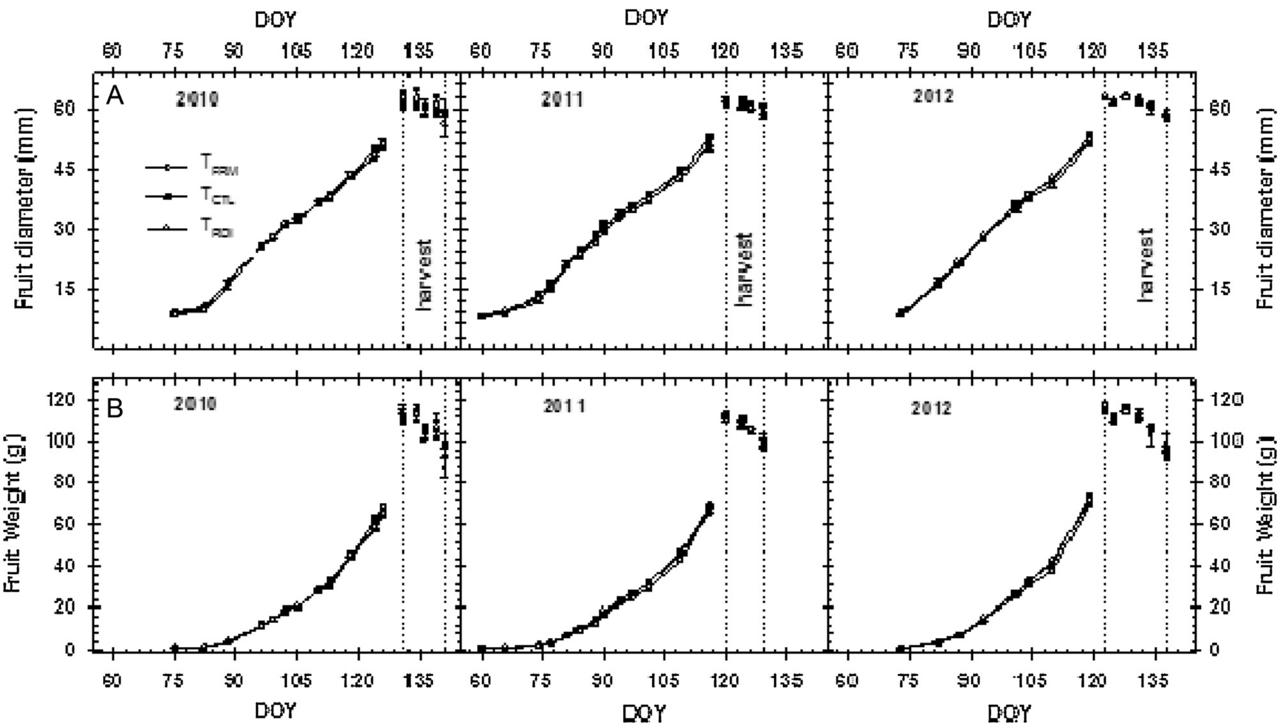

Fig. 5. Seasonal patterns of fruit diameter (A) and fruit fresh weight (B) for the experimental years 2010, 2011 and 2012 for T_{RDI} (—○—), T_{CTL} (—■—) and T_{FRM} (—△—). Each point corresponds to the mean of four replications (thirty fruit per replication) ±SE. Dotted lines delimit the harvest periods. DOY: day of the year.

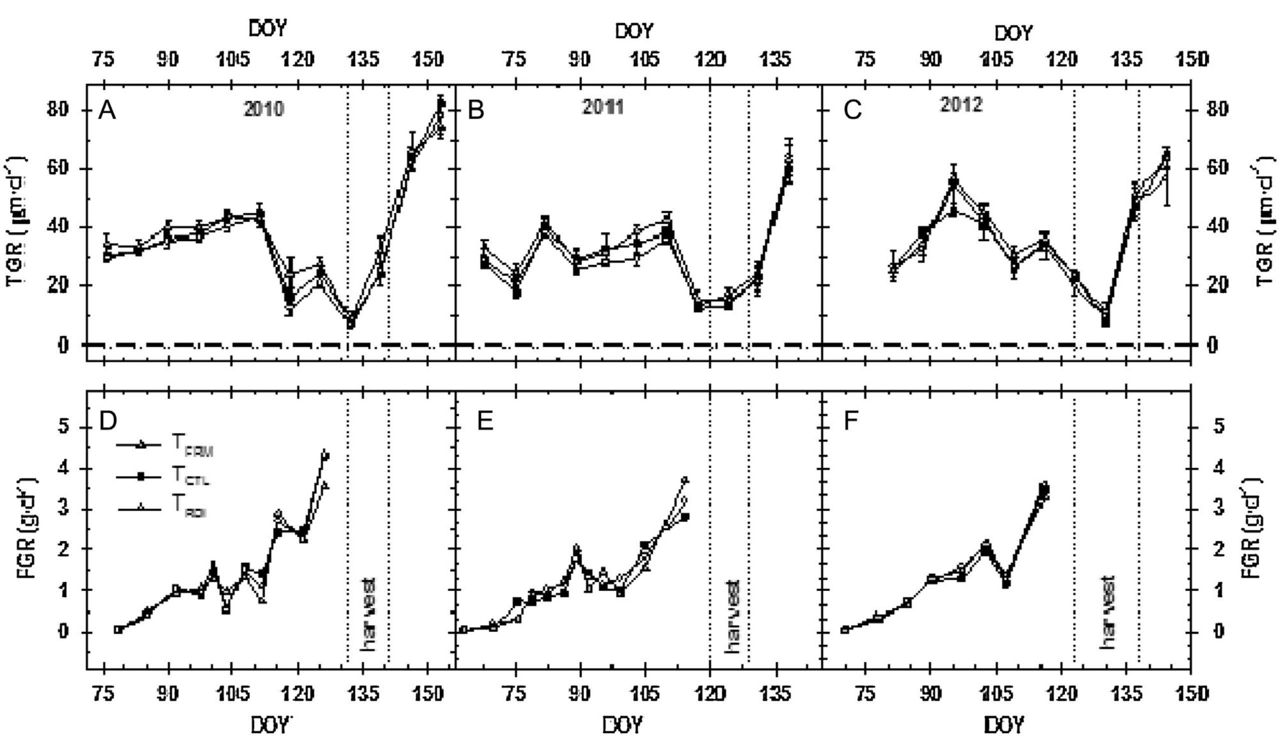

Fig. 6. Seasonal patterns of trunk growth rate (TGR; A, B and C) and fruit growth rate (FGR; D, E and F) during fruit growth and harvest for the experimental years 2010 (A and D), 2011 (B and E) and 2012 (C and F) for T_{RDI} (—○—), T_{CTL} (—●—) and T_{FRM} (—△—). Each point corresponds to the mean of four replications ±SE. Dotted lines delimit the harvest periods. DOY: day of the year.

The different irrigation treatments provided similar yields, crop loads and fruit weights. However, when data were analyzed according to harvest date, the yield and number of fruit showed significant differences between T_{FRM} and the other treatments for the second harvest date in the last year (Fig. 7).

Crop water use efficiency (WUE) of T_{RDI} was higher than that of T_{CTL} and T_{FRM}, by around 25% in 2010 and 2011, and around 74% the final year (Table 1). Interestingly, T_{FRM} increased its WUE from the first year by more than 30%. The productive efficiency was significantly (22%) higher in T_{RDI} than in the control and farmer

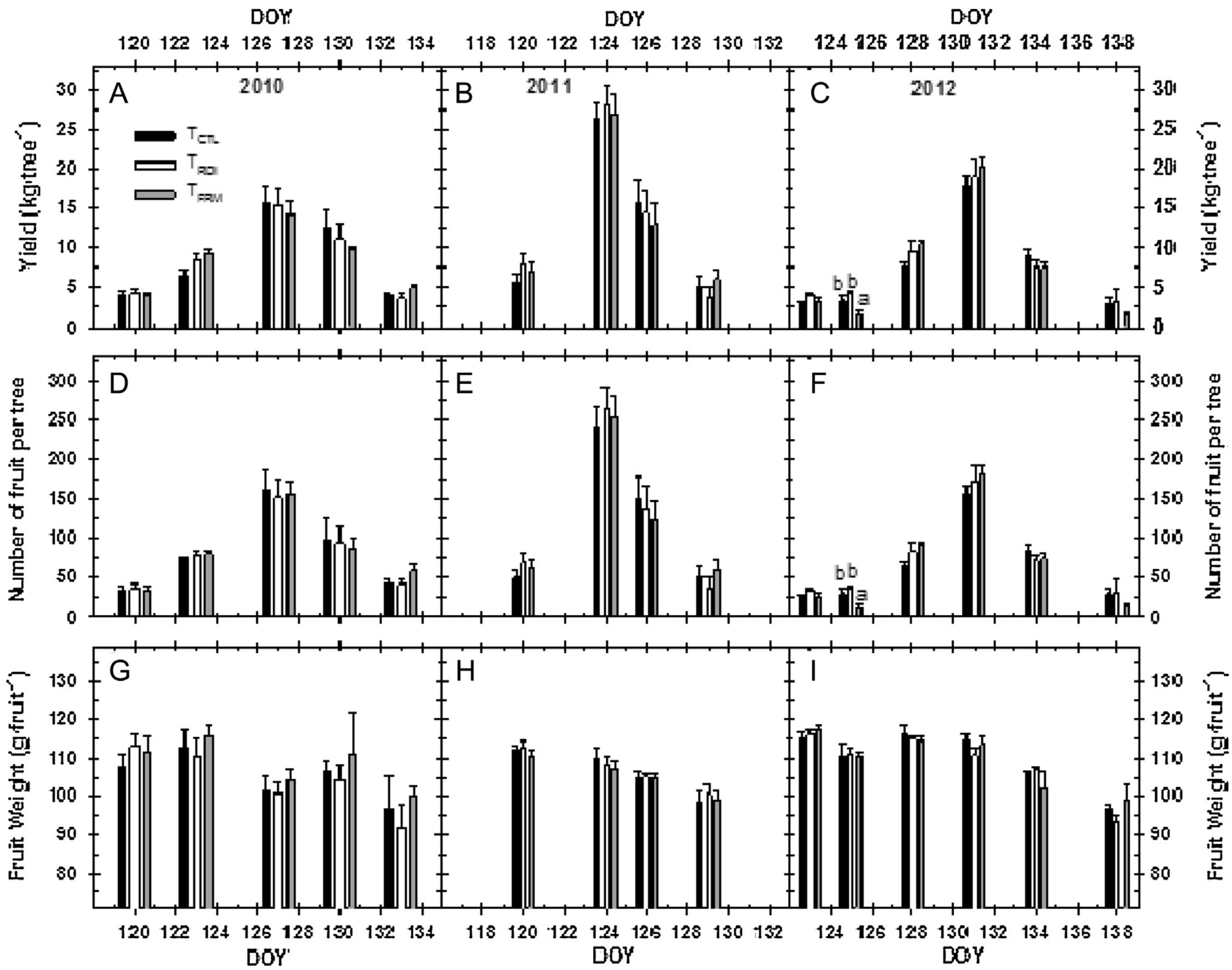

Fig. 7. Fruit fresh yield (A, B and C), number of fruit per tree (D, E and F) and mean fruit fresh weight (G,H, and I) at each harvest date in 2010 (A, D and G), 2011 (B, E and H) and 2012 (C, F and I) for T_{CTL} (black), T_{RDI} (white) and T_{FRM} (gray). Each bar corresponds to the mean four replications (five trees per replication) ± SE. DOY: day of the year.

treatments, but only at the end of the experiment (Table 1). The yield/ΔTCSA ratio always presented higher values in T_{RDI} than in the other treatments as the experiment progressed reaching differences of 53% (Table 1).

Fruit quality determined in nectarine fruits collected on the main harvest date in each year pointed to no significant effect on weight (Fig. 7), fruit diameter, firmness, acidity or soluble solids between irrigation treatments (Table 2).

When different relationships between the annual water stress integral and other variables such as trunk diameter, pruning dry mass, yield and fruit quality were studied, the highest coefficients of determination obtained were with trunk diameter (Fig. 8).

Regarding the interaction between crop level and water deficit, Fig. 9 shows the relationship obtained between the different crop levels and the main yield components and quality traits assessed in this study for T_{CTL} and T_{RDI} during the last two growing seasons (2010–2011 and 2011–2012). As expected, higher crop levels (number of fruits per tree) promoted higher yields (kg per tree^{-1}) (Fig. 9A,B) for the two irrigation treatments. Fruit quality was also affected, the average fruit weight decreasing by around 4.5 g for each extra 100 fruits per tree (Fig. 9C,D), while TSS and the titratable acidity decreased on average by around 0.15% and 0.35 g L^{-1}, respectively, with no significant differences between the irrigation treatments (Fig. 9G–J).

Fruit firmness was the only fruit quality parameter studied that presented significant differences between irrigation treatments, the highest values obtained corresponding to fruits from T_{RDI} trees and lower crop level (Fig. 9E and F).

4. Discussion

The yield response of nectarine cv. 'Flanoba' was insensitive to deficit irrigation until a reduction of 37% of irrigation water was applied compared with the control (T_{CTL}), corresponding to SI_{MDS} values of around 1.5 during postharvest as measured by the LVDT sensors. This underlines the considerable scope for saving water and allows an increase of water use efficiency (WUE) of 70% compared with well-watered trees. Moreover, a positive effect on the management of T_{FRM} was also observed, since in the two last growing seasons the amount of water applied averaged 1600 m^3 ha^{-1} less than that applied in the same treatment during the first season (Table 1). This improvement was due to an agronomic comparison made between treatments by the farmer (no effect on fruit yield and quality when the irrigation water was reduced as the experiment progressed). Of note is that postharvest irrigation scheduling in T_{RDI} during the three-years assayed neither advanced nor delayed the harvest dates with respect to T_{CTL}. Furthermore, the physicochemical characteristics of the fruit evaluated were not altered by deficit irrigation (Fig. 5).

These findings underline the fact that the postharvest period in an early nectarine variety can be considered a non-critical period for the applications of RDI strategies, as can the first and second

Table 2
Average fruit diameter, total soluble solids, Titratable acidity, maturity index and firmness) for the three irrigation strategies (T_{CTL}, T_{RDI} and T_{FRM}) and for each season (2009–2010, 2010–2011 and 2011–2012).

Season		Average fruit diameter (mm)	Total Soluble Solids (%)	Titratable acidity (mg L^{-1})	Maturity index	Firmness (kg 0.5 cm^{-2})
2009/2010	T_{CTL}	60.4	8.5	11.4	7.3	5.0
	T_{RDI}	60.1	8.3	10.7	7.8	4.5
	T_{FRM}	60.8	8.4	10.7	7.9	4.7
	A_{NOVA}	ns	ns	ns	ns	ns
2010/2011	T_{CTL}	60.9	7.9	9.7	8.1	4.1
	T_{RDI}	60.9	8.1	10.0	8.1	3.6
	T_{FRM}	61.0	7.7	9.6	8.0	3.3
	A_{NOVA}	ns	ns	ns	ns	ns
2011/2012	T_{CTL}	60.9	8.7	11.2 b	7.8	5.8
	T_{RDI}	60.9	9.0	10.9 ab	8.3	6.1
	T_{FRM}	60.9	8.8	10.6 a	8.3	5.9
	A_{NOVA}	ns	ns	0.046	ns	ns

ns, not significant. Means for each column followed by different letter are significantly different at $P < 0.05$, according to Duncanís multiple range test after irrigation effects were shown to be significant by ANOVA test with $P < 0.05$.

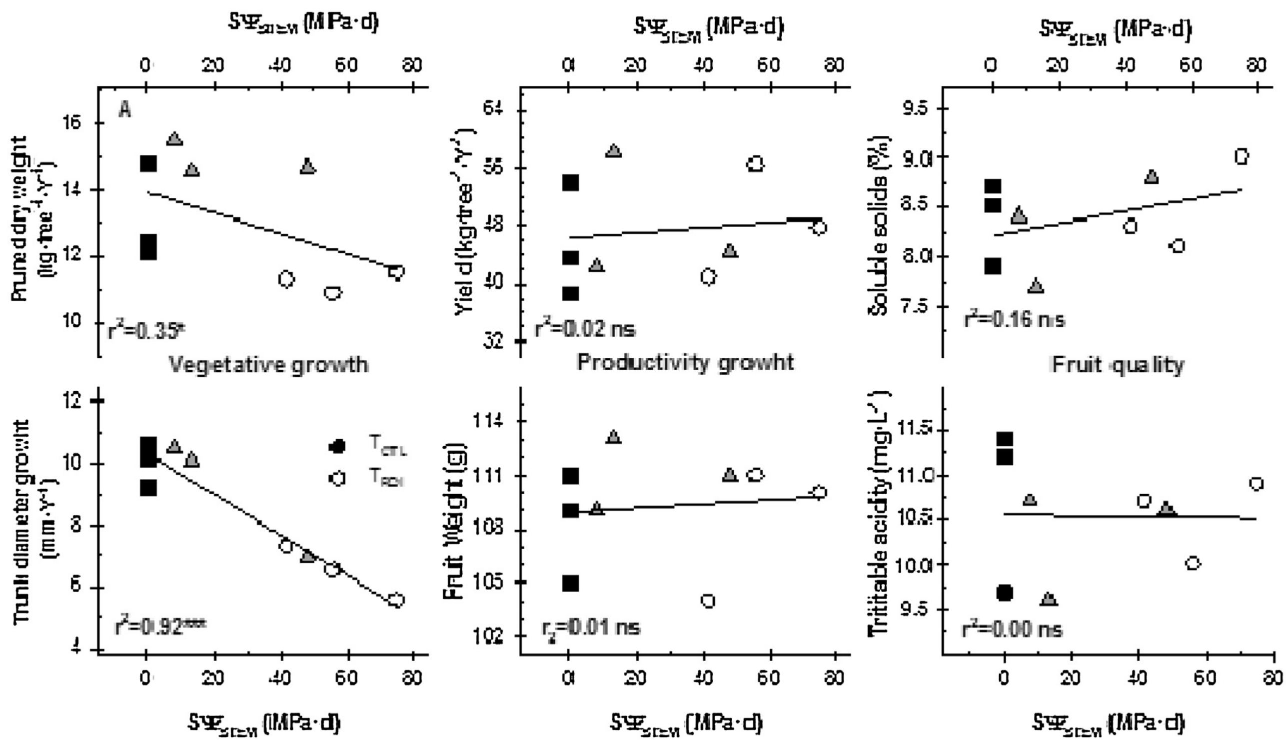

Fig. 8. Relationship between annual water stress integral and vegetative growth (Pruning dry mass—A; Trunk diameter growth—D), productivity growth (Yield—B; Fruit weight—E) and fruit quality (Soluble solids—C; Total acidity—F). Each point corresponds to an average per year for the irrigation strategies T_{RDI} (○), T_{CTL} (■) and T_{FRM} (△).

fruit growth stages according to previous studies in peach (Ruiz-Sánchez et al., 2010), in nectarine (Thakur and Singh, 2012) and in apricot trees (Pérez-Pastor et al., 2015). In this sense, threshold values of Ψ_{stem} of about −1.5 and −2.0 MPa during the postharvest were recommended to ensure no impairment of bloom fertility (Girona et al., 2005) and to limit the occurrence of double fruits (Naor et al., 2005), respectively. Moreover, in our early-ripening nectarine cultivar a water stress level was very difficult to implement during the fruit growth period, since it coincided with low water demand and several rainfall events (from March to beginning of April). However, it was possible to apply a water stress 15-days after ripening without negatively affecting tree yield, as mentioned by Pérez-Pastor et al. (2009) in apricot and Girona et al. (2005) in peach trees, while improving the fruit quality at harvest and after cold storage in both crops (López et al., 2011; Pérez-Pastor et al., 2007). When RDI is applied, it is essential not only to identify these non-critical periods but also to determine the intensity and the timing of the water stress imposed within any non-critical period (postharvest in our case) to avoid adverse effects on the following harvest and on vegetative growth.

Vegetative growth was sensitive to deficit irrigation, as many researchers have reported in deciduous fruit trees (Boland et al., 1993; Caspari et al., 1994; Girona et al., 2005; Pérez-Pastor et al., 2014; Rahmati et al., 2015). This was confirmed in our experiment by the strong correlation between the increase in the water stress integral obtained by Ψ_{stem} and the reduction in TSCA (Fig. 8). Furthermore, during the first two growing seasons, the vegetative growth was reduced in T_{RDI}, corresponding to water savings of around 15%, although during the third year, this reduction was greater at around 40% involving 37% water saving, due to the more prolonged reduction of water applied compared with the first two growing seasons, in both cases without penalizing the yield and quality, as above indicated. Chalmers et al. (1984) found that deficit irrigation applied from the early stages of fruit growth until the

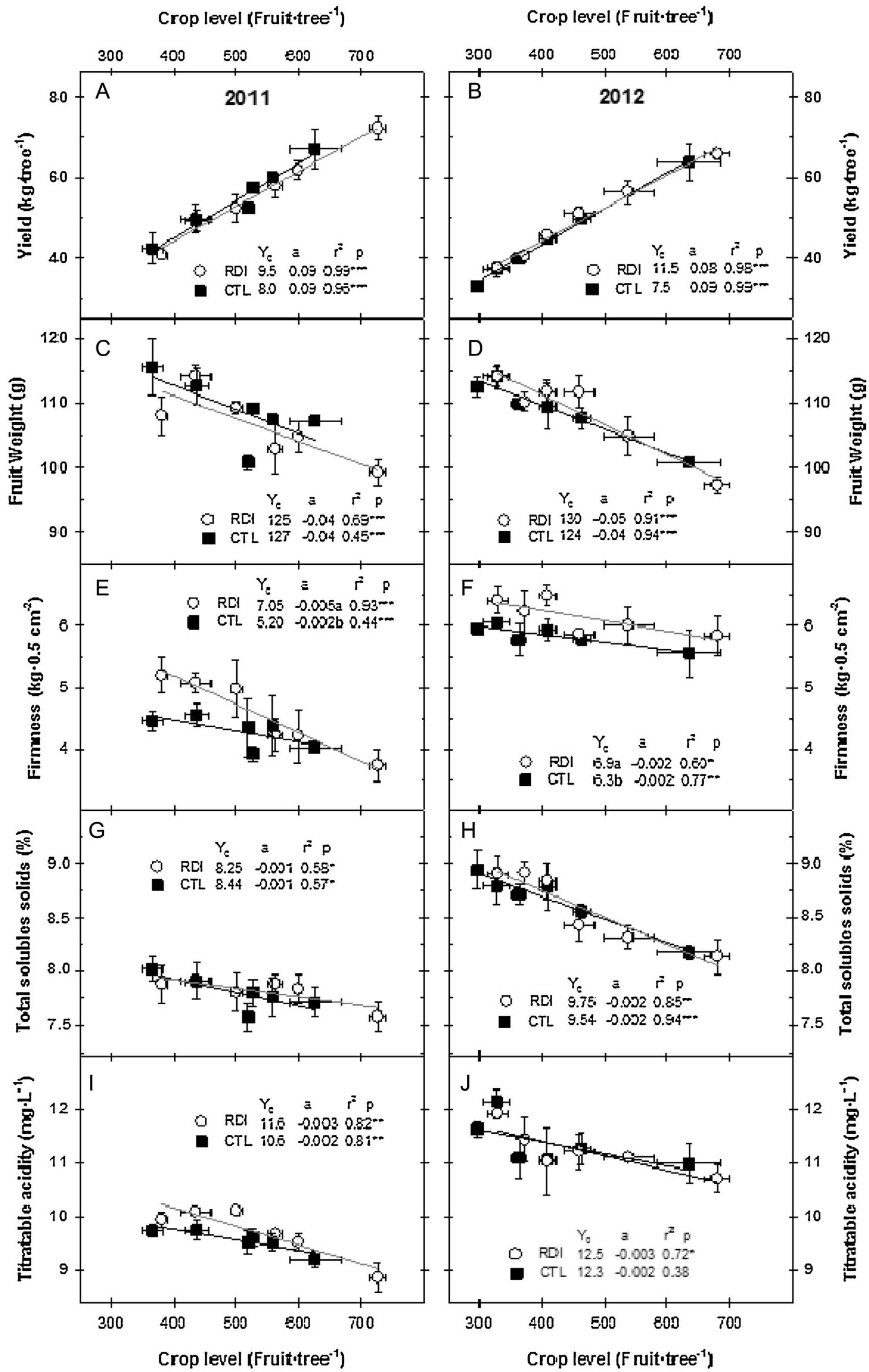

Fig. 9. Relationship between crop level and: yield (A and B); Fruit weight (C and D); Firmness (E and F); Total soluble solids (G and H) and Titratable acidity (I and J) for the irrigation strategies T_{RDI} (◯) and T_{CTL} (■) and for the experimental years 2011 (A, C, E, G and I) and 2012 (B, D, F, H and J). Each point represents the average of three replicates (1 tree per replication) ± SE.

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end of shoot growth affected vegetative growth by inhibiting shoot development, but did not affect the final yield or fruit size. However, when the intensity and duration of the water stress imposed are severe, the vegetative growth may reduce the total yield per tree by reducing the number of fruits due to the reduction in tree size (Pérez-Pastor et al., 2014). In apricot trees, the authors determined the correct intensity and timing to avoid any negative influence of the water deficit during the non-critical period (post-harvest), and suggested that RDI led to yield reductions as a consequence of the decrease in the number of fruits per tree due to the reduction in vegetative growth, but only when water deficits promoted water stress integral values higher than 140 MPa day, which provided a water saving of > 46% with respect to well-watered-trees.

More particularly, the nectarine cultivar studied presented high vegetative growth just after harvest (from May to June), as Figs. 2 and 6 show, and as indicated by the pruning weight, which was higher in early summer than in autumn, increasing with the level of the irrigation water applied (Figs. 3 and 8). These results agree with previous reports in almond (Romero et al., 2004), in pear (Mitchell et al., 1989), and in peach (Boland et al., 1993; Girona et al., 2005; Johnson et al., 1992). Controlling vegetative growth can also be positive in the sense that deficit irrigation reduces labor costs (López et al., 2008). However, a water deficit applied from the end of May involved a substantial reduction in vegetative growth and was potentially harmful because of the decrease in tree size and, hence, the possibility of lower subsequent yields. Our findings showed that water stress integral and trunk growth rate values registered in June must be lower than 10 MPa day and around 50 μm day^{-1}, respectively (Figs. 1 and 2), in order to not affect vegetative growth. The competition between vegetative growth and fruit (Bevington and Castle, 1985) in the days preceding harvest can be seen in Fig. 6. However, such competition is only possible during the short period of fruit growth and ripening (50 days), since throughout postharvest, vegetative growth does not compete with fruit growth. Ruiz-Sanchez et al. (2010) indicated that a clear separation between the main periods of vegetative growth and fruit growth is an advantageous feature for the successful implementation of RDI in fruit. In addition, the non-critical post-harvest period coincides with the months of greatest evaporative demand, so the margin for saving water is high. Moreover, the significantly higher values of the ratio between yield and ΔTCSA in T_{RDI} than in the T_{CTL} and T_{FRM} during the three years of the experiment indicated that carbon partitioning was mainly dedicated to fruit growth at the expense of reduced vegetative growth.

Crop level affected the total yield and fruit quality, so that fruit thinning can be considered as a technique for improving fruit composition (Alcobendas et al., 2012). As expected, the average fruit weight decreased with higher crop levels, due to the higher competition between fruits for photoassimilates (Berman and DeJong, 1997) and the lower leaf:fruit ratio (Grossman and Dejong 1995). Besides, TSS decreased as the crop level increased, as found in peach (Lopez et al., 2012). However the behaviour of both firmness and titratable acidity was contrary to some results published for apricot (Southwick et al., 1995) and sweet cherry trees (Usenik et al., 2008). These differences might be due to the early maturation of the nectarine trees studied in this experiment.

The irrigation treatments (T_{RDI} and T_{CTL}) did not alter relations between crop level and fruit yield and quality. Only firmness was significantly greater in T_{RDI} trees with a lower crop level. In this sense, Alcobendas et al. (2012) suggested other factors, such as exposure to sunlight, should be taken into consideration in order to compensate the possible negative effects of deficit irrigation on fruit size.

As observed in this work, the postharvest period in early nectarine trees can be considered as non-critical for applying RDI strategies, although the water stress integral level applied should be lower than 9 MPa day per month during the months following harvest (May and June), when vegetative growth is greatest in this crop. In other words a mild water stress must be applied since this is when vegetative growth is greatest. Higher water stress levels would negatively affect the subsequent harvest by reducing the number of fruits per tree. After this period the water stress integral level can be higher, coinciding with the period of greater water demand (from July to September).

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