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Response of peach trees to regulated deficit irrigation during stage II of fruit development and summer pruning

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Abstract

Regulated deficit irrigation (RDI) during stage II of fruit development and summer pruning (watersprout removal, WSR) can be used to control excessive vegetative growth in high-density peach orchards. The dynamics of tree-light interception after the application of RDI (no irrigation during stage II) and WSR in summer were evaluated during two consecutive years. RDI and WSR treatments produced similar reductions in the percentage of light intercepted by the tree at the end of the 2-year experiment. However, it was not possible to produce the same seasonal dynamics in the percentage of light intercepted by the tree using the RDI and the WSR techniques; RDI trees showed a gradual reduction in the amount of light intercepted as the productive cycle progressed, while WSR trees showed an immediate reduction in the amount of light intercepted. Moreover, the mechanisms responsible for vegetative growth reduction were different in the RDI and the WSR techniques. The RDI technique was associated with reductions in tree water status and decreases in gravimetric soil water (θg) and fruit growth capacity. RDI may have reduced θg below the threshold required for optimum fruit growth, whereas WSR reduced water consumption, improved water status and therefore could have benefited fruit growth. Therefore, RDI and WSR greatly differ when the mechanisms responsible for vegetative growth reduction are taken into consideration.

Additional key words: crop load, fruit quality, light interception, *Prunus persica* L. Batsch, soil water, stem water potential, water stress.

Resumen

Respuestas del melocotonero al riego deficitario controlado durante la fase II de crecimiento del fruto y a la poda de verano

El riego deficitario controlado (RDI) durante la fase II de crecimiento del fruto y la poda de chupones en verano (WSR) podrían usarse para controlar el exceso de crecimiento vegetativo en plantaciones de melocotonero de alta densidad. Se estudió el papel de la reducción en la radiación interceptada por el árbol tras la aplicación de un RDI durante la fase II (supresión total de riego) y la WSR durante dos años consecutivos. Ambas técnicas produjeron una reducción similar en la radiación interceptada por el árbol al final del experimento. Sin embargo, la dinámica estacional de la radiación interceptada por el árbol fue diferente entre WSR y RDI. La WSR produjo una disminución inmediata en el porcentaje de radiación interceptada por el árbol, mientras que el RDI produjo una disminución paulatina a medida que avanzó la campaña. Además, los mecanismos promotores de la reducción del crecimiento vegetativo fueron diferentes. El RDI afectó negativamente al estado hídrico del árbol, a la cantidad gravimétrica de agua en el suelo (θg) y al crecimiento del fruto. Mientras que el RDI parece reducir el θg por debajo del umbral necesario para obtener un crecimiento de fruto óptimo, una disminución en el consumo de agua tras la WSR habría mejorado el estado hídrico del árbol para finalmente beneficiar el crecimiento del fruto. Aunque el RDI y la WSR produjeron una reducción similar en el porcentaje de radiación interceptada por el árbol, ambas técnicas muestran claras diferencias cuando se analizan los factores relacionados con la reducción en el crecimiento vegetativo.

Palabras clave adicionales: calidad del fruto, carga de frutos, contenido de agua en el suelo, estrés hídrico, potencial hídrico de tallo, *Prunus persica* L. Batsch, radiación interceptada.

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Introduction

Water is becoming scarce in the Mediterranean area where agriculture accounts for the vast majority of consumptive water use. It is therefore necessary to develop and implement regulated deficit irrigation (RDI) techniques in order to optimize water use without affecting crop yields. Although water stress has a negative effect on most agricultural crops, fruit trees seem to adapt well to deficit irrigation (Costa *et al.*, 2007). For example, peach (*Prunus persica* L. Batsch) trees permit the implementation of RDI during stage II of fruit development, which is known to be quite insensitive to water stress (Chalmers *et al.*, 1981; Li *et al.*, 1989; Girona *et al.*, 2004). Moreover, since stage II coincides with high rates of vegetative growth and shoot expansion, these are among the earliest responses to water stress (Bradford and Hsiao, 1982). Moderate water stress during stage II reduces tree crown development (Mitchell and Chalmers, 1982; Boland *et al.*, 2000). This reduction in vegetative growth is desirable in high-density orchards. Such is the case of high-density peach orchards, where it is necessary to control vegetative vigour in order to optimize tree-light interception and to improve the economic success of the orchards (Chalmers *et al.*, 1981). It would therefore seem feasible to: impose moderate water stress during stage II of fruit development in high-density peach orchards, conserve existing water resources, reduce excessive vegetative growth, and avoid any negative effect on total crop yield.

Since RDI was first adopted in peach orchards, many studies have shown that its application during stage II of fruit development provides beneficial effects for peach trees (Chalmers *et al.*, 1981; Mitchell and Chalmers, 1982; Li *et al.*, 1989; Williamson and Coston, 1990; Boland *et al.*, 1993, 2000; Girona *et al.*, 2003, 2005; Gelly *et al.*, 2004). However, this is not always the case, and a number of authors have reported negative influences on fruit growth capacity when RDI was applied during stage II (Girona, 1989, 2003; Goldhamer *et al.*, 2002). As Johnson and Handley (2000) pointed out, this lack of consistence in RDI experiments may be dispelled with a better understanding of how water stress affects physiological processes in plants.

There are still many physiological processes related to phenological sensitivity to water stress that are not fully understood (Marsal *et al.*, 2006). One of these processes relates to how moderate water stress affects the dynamics of tree-light interception as a consequence of a reduction in vegetative growth (none of the previously cited RDI experiments reported seasonal variations in the amount of light intercepted by the tree). Taking into account the fact that RDI seems to have reduced vegetative growth in the vast majority of experiments (Girona, 2002), we hypothesized that the effects of RDI on tree-light interception could be comparable to those obtained after summer pruning (Marini, 1985; DeJong and Day, 1991; Myers, 1993) if a similar reduction in vegetative growth was achieved with each technique. On the other hand, the way in which this vegetative growth reduction was obtained differed between RDI and summer pruning, and this may have been accompanied by differences in some of the mechanisms associated with the particular technique applied. A comparison between RDI and summer pruning under the same orchard conditions may therefore help to distinguish between the effects related to RDI and those related to the reduction in vegetative growth. This should offer a better understanding of the physiological basis behind RDI and the extent to which it could be used in the near future.

The objectives of this research were: (1) to determine whether it was possible to achieve similar reductions in tree-light interception using RDI and summer pruning practices in peach trees, and (2) to compare the effects of RDI and summer pruning on the physiological processes that may be associated with a reduction in vegetative growth. The latter include tree water status, fruit growth capacity, tree water uptake, flowering and fruit set, and fruit quality.

Material and Methods

Experimental plot

The experiment was conducted over two years (2003-2004) at a commercial orchard in Huesca province

Abbreviations used: CP (commercial summer pruning), DW (mean fruit dry weight), ET_c (crop water use), ET_o (reference evapotranspiration), FB (full bloom), FF (flesh firmness), FI (full irrigation), FW (mean fruit fresh weight), K_c (crop coefficient), LSM (least square means), m.a.s.l (meters above sea level), PAR (photosynthetically active radiation), RDI (regulated deficit irrigation), RDM (relative dry matter), SD (standard deviation), SE (standard error), SSC (soluble solid content), TA (titratable acidity), WSR (watersprout removal), ψ_{stem} (stem water potential), θg (gravimetric soil water).

(41.6°N, 0.26°E, 295 m a.s.l), Spain. The soil had a loamy texture and was more than 2 m deep. Cumulative precipitation during the 2003 and 2004 growing seasons was 24.5 and 65.8 mm, respectively. There was no precipitation during stage II of fruit development and high summer temperatures (> 34°C) were registered during the 2-year experiment. We monitored 63 peach trees of a mid-to-late-maturing cultivar (*Prunus persica* L. Batsch cv. O'Henry). The trees were 5 years old and were grafted onto GF 677 hybrid rootstock. Between-row spacing was 5 m and within-row spacing was 3 m. The trees were trained to a vase system. The plot had an automated drip irrigation system with four pressure-compensating emitters (2 L tree^{-1} h^{-1}). The trees were irrigated daily. Tree water requirements were calculated using a water balance technique in order to replace the water consumed by the trees: effective rainfall was subtracted from crop water use (ET_c). Crop water use was calculated as $ET_c = ET_o \times K_c$ (Allen *et al.*, 1998). ET_o and K_c represent the reference evapotranspiration and crop coefficient, respectively. The Penman-Monteith method (Allen *et al.*, 1998) was used to determine reference evapotranspiration (ET_o) and crop coefficients (K_c) were estimated as described by Doorenbos and Pruitt (1977). The orchard was daily irrigated. Pre-bud-break sprinkler irrigation was applied to refill the soil profile and thereafter the amount of water applied during the growing season was monitored with a multi-jet water meter (Model D85, Wehrle, Emmendingen, Germany). The orchard was managed according to commercial practices, including mechanized summer pruning, fruit thinning midway through stage II of fruit growth, and late-winter pruning (February) to maintain appropriate tree shape.

Treatments and experimental design

Two irrigation treatments were applied during stage II of fruit development: full irrigation (FI) and no irrigation (RDI). During the rest of the season trees from both treatments were fully irrigated. At the end of stage II of fruit development, two summer pruning treatments were alternatively applied: commercial pruning (CP) and watersprout removal (WSR). The CP consisted of mechanized topping. The WSR consisted of eliminating all the watersprouts growing on the main scaffolds. The vegetation removed by pruning was weighed.

A randomized complete block design with three block-replicates was used. Three treatment combinations were randomly assigned to elemental plots within blocks. These combinations were FI + CP, FI + WSR, and RDI+ CP. Each elemental plot consisted of a row of seven trees. Each elemental plot was surrounded by border trees.

Measurements

The percentage of the area covered by the tree was determined on a weekly basis by measuring irradiance at ground level in the shaded area below the tree crown, using a linear ceptometer (probe length 80 cm; Accupar Linear PAR; Decagon Devices, Pullman, WA, USA) as described by Klein *et al.* (2001). Measurements were taken at solar noon ± 30 min on completely clear days, from stage II of fruit growth until harvest in each of the two experimental years. Measurements were taken in all the experimental trees. For each tree, eight radial measurements were made below the tree crown, separated by angles of 45°, centred at the base of the trunk and on which the end of the ceptometer was placed. On each occasion, a measurement was also made in an open area with no interference from the tree crown. The percentage of photosynthetically active radiation (PAR) intercepted by the tree was estimated from noon light readings taken under the canopy, which was expressed as:

$$\text{PAR (\%)} = 100\left[1 - \frac{\text{mean value below the tree crown}}{\text{value outside the tree crown}}\right] \quad [1]$$

To evaluate tree water status, stem water potential (Ψ_{stem}) was determined on a weekly basis throughout the fruit growing season in each of the two experimental years. This was done with a pressure chamber (model 3005; Soil Moisture Equipment Corp., Santa Barbara, CA) and as outlined by McCutchan and Shackel (1992). Measurements were taken at solar noon ± 30 min on a leaf located near the bases of two central trees of each elemental plot.

Random samples of two fruits per tree were taken on a weekly basis throughout the fruit growing season in each of the two experimental years. Samples were taken in all the experimental trees. The dry mass of each sample was calculated after drying it to a constant mass in a forced-air draft oven at 70°C. Individual fruit fresh weight (FW) and individual fruit dry weight (DW) were estimated by dividing the total fresh or dry mass of a sample from a given tree by the number of fruits in the sample. Fruit relative dry matter (RDM) was calculated as:

$$\mathrm{RDM}\ (\%) = \frac{\mathrm{DW}}{\mathrm{FW}} \quad [2]$$

Fruits were harvested according to commercial peach colour. In 2003, fruits were harvested in two consecutive picks (August 22nd and 27th). In 2004, fruits were harvested in three consecutive picks (August 24th and 31st, and September 3rd). The number of fruits per tree and their total fresh mass were determined at each harvest and for every experimental tree. Total yield was then calculated as the sum of the total fruit fresh mass at each harvest.

To evaluate the effects of the treatment combinations on soil water content, soil samples were taken at harvest time in 2004. Twenty-six experimental trees representative of each treatment were selected. The soil samples were taken from the area between the trunk of the selected trees and the nearest irrigation dripper. They were taken at several depths in the root zone (40, 60, and 80 cm), using a soil auger with a removable sleeve. The samples were weighed immediately after extraction to minimize water loss. The dry weight of each sample was calculated after drying it to a constant mass in a forced-air draft oven at 105ºC. Soil water was determined on a gravimetric basis (θg) as:

$$\theta g\ \ (\%) = 100\left(\frac{\text{sample fresh weight} - \text{sample dry weight}}{\text{sample dry weight}}\right) \quad [3]$$

After winter pruning, four fruiting shoots from each tree were randomly selected and tagged, and their shoot lengths were determined. The number of flowers on each fruiting shoot was determined at full bloom (FB). In 2004, the estimated FB date (the estimated time when 50% of the flowers in the orchard were fully open) was March 25th. The number of fruits on each tagged fruiting shoot was determined 30 days after FB and also both before and after commercial fruit thinning.

Six fruits per tree were sampled for quality analysis just before harvest. Fruits were then stored for one week at 0°C and 90% relative humidity. After cold storage, fruit quality analysis was carried out as outlined by Gelly *et al.* (2004). Fruit skin colour was measured with a photoelectric tristimulus colorimeter (CR-200, Minolta Co., Osaka, Japan). The colorimeter was calibrated with a white standard before use. Three measurements were taken for opposite fruit cheeks and then averaged for each cheek. Fruit chromaticity was recorded in CIELAB (International Commission on Illumination) colour coordinates (L*, a*, and b*). Hue angle, which can be used to quantify colour, was calculated as arctangent (b*/a*). A 90° hue angle represents yellow, 180° represents bluish-green, 270° represents blue, and 0° represents reddish-purple (McGuire, 1992). Fruit flesh firmness (FF) was evaluated on two opposite peeled surfaces using an Effegi penetrometer with an 8 mm tip (Effegi, Milan, Italy). FF data were expressed in terms of N. Soluble solid content (SSC) and titratable acidity (TA) were determined from a blended composite of wedges obtained from the 42 peaches per elemental plot. An undiluted fluid fraction was used to determine SSC concentration using a digital calibrated refractometer (Atago Co, Tokyo, Japan). SSC data were expressed in °Brix. TA was determined for the same composite by titrating to an end-point pH 8.1 with 0.05 M NaOH and was expressed as g malic acid L^{-1}.

Statistical analyses

The effects of the different treatment combinations on the ψ_{stem}, FW, DW and RDM for each of the two experimental years were analysed by repeated measure analysis of variance (ANOVA) over time. The effects of different treatment combinations on total fruit fresh mass at harvest for each of the two experimental years were evaluated by analysis of covariance (ANCOVA), which tested for heterogeneity in the slope of treatment combination responses to fruit load. The effect of fruit load on mean θg within the soil profile at harvest time (2004) was analysed by ANCOVA. The effect of the different treatment combinations on fruit quality were analysed by ANOVA. Analyses were performed using the SAS software package (SAS Institute, Cary, NC). Statistical significance was established for $P < 0.05$. Tukey's test was applied for separation of the least square means (LSM) of treatment combinations that differed significantly.

Results

The amount of water applied during the growing season was greater in 2003 than in 2004 because of a water shortage in 2004. In 2003, trees in the FI treatment received 605 mm, whereas those in the RDI treatment received 510 mm. In 2004, trees in the FI treatment received 455 mm, while those in the RDI treatment received 364 mm. The differences in water supply between the FI and RDI treatments reflected the different amounts of water delivered during stage II of fruit development: trees under RDI received no irrigation during stage II of fruit development.

In 2003, the amount of vegetative fresh mass removed by summer pruning was 3.43 kg tree^{-1} (standard deviation SD = 1.02), 0.54 kg tree^{-1} (SD = 0.09), and 0.36 kg tree^{-1} (SD = 0.04) for the FI + WSR, FI + CP and RDI + CP treatment combinations, respectively. In 2004, the amount of vegetative fresh mass removed by summer pruning was 2.11 kg tree^{-1} (SD = 0.49) and 0.33 kg tree^{-1} (SD = 0.03) for the FI + WSR and FI + CP treatment combinations, respectively. The vegetation removed by pruning in the RDI + CP treatment combination was not significant.

The treatment combinations caused significant changes in the percentage of PAR intercepted (Fig. 1). In 2003, the RDI + CP treatment combination was associated with a progressive decrease in PAR interception during stage II of fruit development, with respect to the FI + CP and FI + WSR treatment combinations. After summer pruning (~end of stage II), all the treatment combinations produced an immediate decrease in the percentage of PAR intercepted, although FI + WSR trees showed the greatest reductions (~10%). In 2004, significant differences were observed between the percentages of PAR intercepted by different treatment combinations at the onset of stage II of fruit development; FI + WSR and RDI + CP trees exhibited lower values of intercepted PAR than FI + CP trees, and these differences were maintained throughout stage II. After summer pruning (~end of stage II), FI + WSR and RDI + CP trees exhibited similar values of PAR interception during the period between pruning and harvest.

Withholding irrigation during stage II of fruit development significantly reduced midday ψ_{stem} in RDI + CP trees in each of the two experimental years (Fig. 2, Table 1); in 2003 and 2004, midday ψ_{stem} for RDI+CP trees reached minimum values of –1.40 and –1.00 MPa, respectively. Water status for RDI + CP trees fully recovered following deficit irrigation during stage II (Fig. 2). The FI + WSR treatment produced the most improved tree water status during the 2-year study, but its effects on the ψ_{stem} did not significantly differ from those of the FI + CP treatment (Table 1).

Before application of the different treatments, there were no significant differences between experimental trees in terms of FW, DW and RDM (Fig. 3). The treatment combinations caused significant changes in seasonal variations in FW, DW, and RDM (Fig. 3, Table 2). Although seasonal variations in FW and DW were similar for both experimental years (Fig. 3), the effect of the treatment combinations on FW and DW

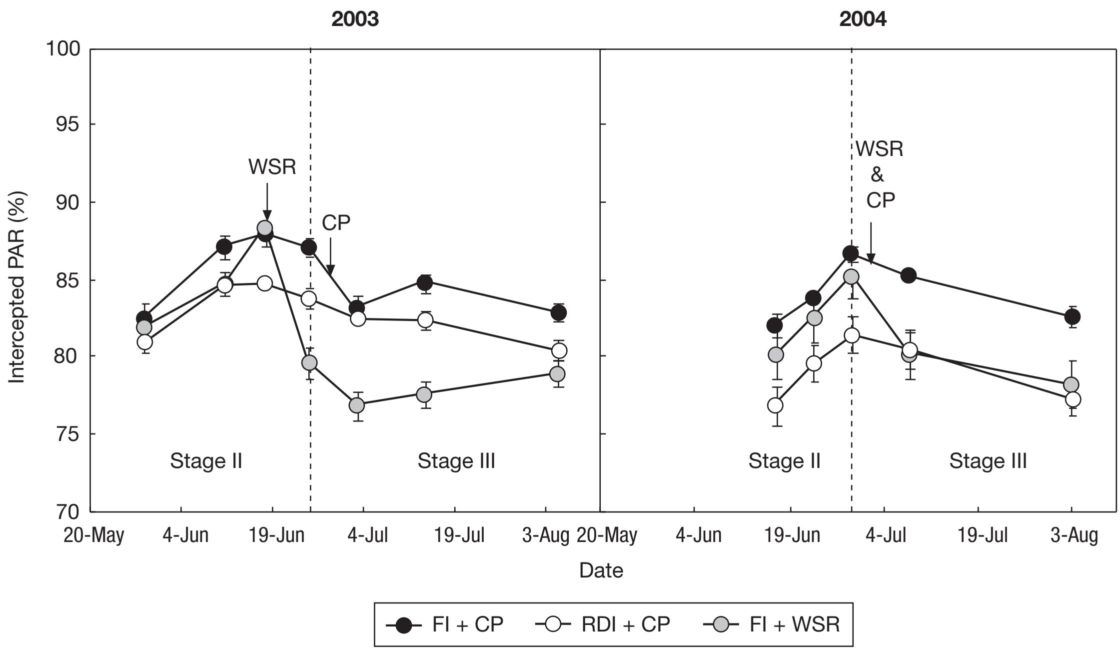

Figure 1. Seasonal variations in percentage of photosynthetically active radiation (PAR) intercepted by the tree in response to irrigation and summer pruning treatments. Each value is the mean for 21 trees ± SE. FI: full irrigation. CP: commercial summer pruning. RDI: no irrigation during stage II of fruit development. WSR: watersprout removal.

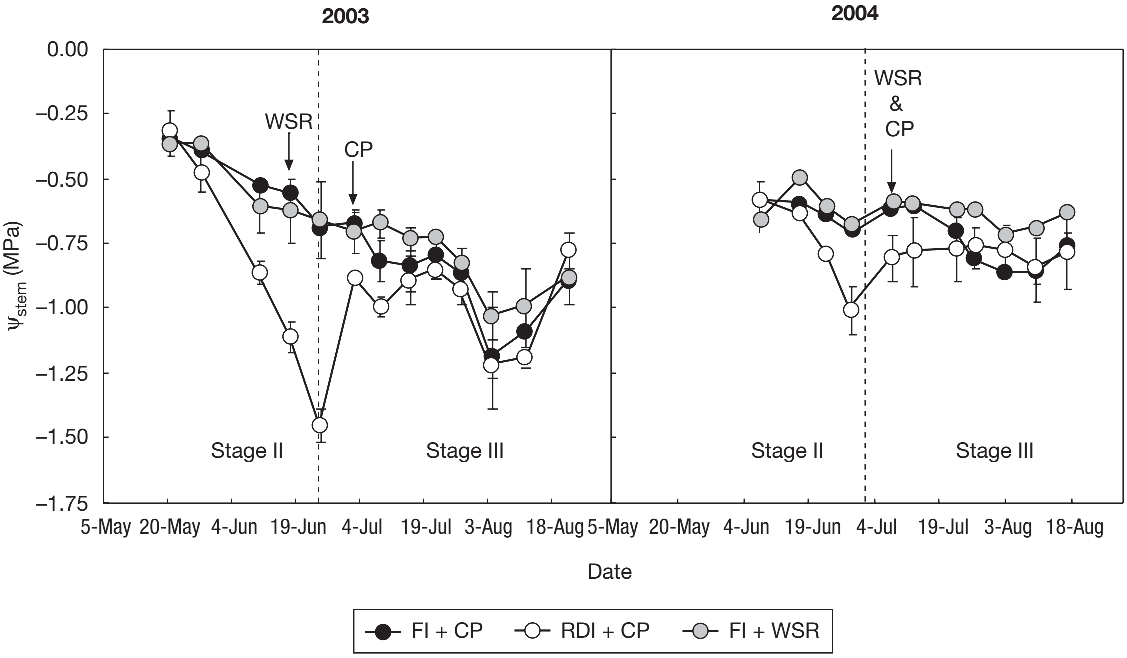

Figure 2. Seasonal variations in midday stem water potential (ψ_{stem}) in response to irrigation and summer pruning treatments. Each value is the mean of six trees ± SE. FI: full irrigation. CP: commercial summer pruning. RDI: no irrigation during stage II of fruit development. WSR: watersprout removal.

was more evident in 2004 (Table 2); RDI + CP trees had the lowest FW and DW values, whereas FI + CP trees had the highest values. RDM during stage II of fruit development was significantly higher in RDI + CP trees than in FI + CP and FI + WSR trees in each of the two years (Fig. 3C, 3F; Table 2). These differences in RDM did not disappear immediately after relief from water stress. In 2003, it took six weeks of full-irrigation during stage III to equalize RDM values between treatments (Fig. 3C). In 2004, however, fruits from the RDI irrigation treatment did not reach full hydration at harvest (Fig. 3F). The FI + WSR treatment produced the lowest values of RDM in each of the two experimental years (Table 2).

Table 1. Effect of treatment combinations, sampling time and the interaction beween treatment combinations and sampling time on midday stem water potential (ψ_{stem}), analyzed by repeated ANOVA measures over time

Effects on ψ_{stem}	2003	2004
Probability		
Treatment combinations	0.0001[1]	0.0001
Time	0.0001	0.0001
Treatment × time	0.0001	0.7850
LSM for the treatment combinations (MPa)		
FI + CP	–0.76 a[2]	–0.71 a
FI + WSR	–0.72 a	–0.63 a
RDI + CP	–0.93 b	–0.83 b

[1] Probability according to the repeated measures ANOVA over time. [2] Means followed by different letters in the same column are significantly different at 5% according to Tukey's test. LSM: least square means. FI: full irrigation. CP: commercial summer pruning. WSR: watersprout removal. RDI: no irrigation during stage II of fruit development.

Although all the trees received commercial fruit thinning, the fruit loads of the trees within each treatment combination were somewhat variable (Fig. 4); fruit load ranged from 90 to 450 fruits tree^{-1}. The effect of fruit load on total fruit fresh mass at harvest was significant for trees in all of the treatment combinations and for both experimental years (Table 3); fruit fresh mass increased with fruit load (Fig. 4). In 2003, there were no significant differences between treatment combinations in terms of total fruit fresh mass (Table 3, Fig. 4). In 2004, however, the slope for total fruit fresh mass response to fruit load in the FI + CP and FI + WSR treatment combinations was steeper than for the RDI + CP treatment combination (Table 3, Fig. 4).

Application of the treatment combination during two consecutive years affected the soil water content at the end of the experimental period (harvest 2004)

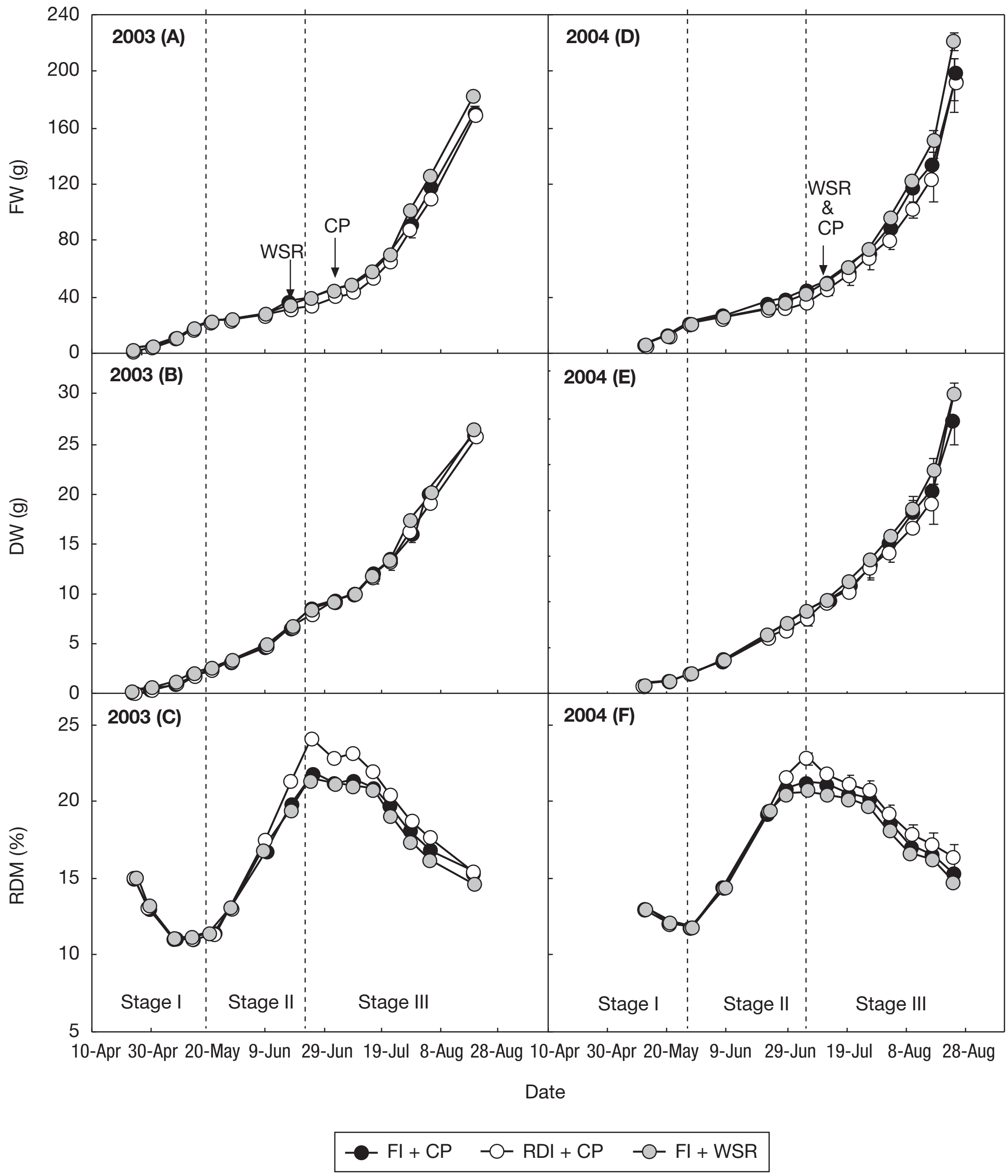

Figure 3. Seasonal variations in fruit fresh weight (FW), fruit dry weight (DW), and relative dry matter (RDM). Each value is the mean for two fruits (n = 21 trees) ± SE. FI: full irrigation. CP: commercial summer pruning. RDI: no irrigation during stage II of fruit development. WSR: watersprout removal.

(Fig. 5). The FI + WSR treatment combination showed θg values of around 13% throughout the soil profile; the FI + CP treatment combination was associated with a considerable decrease in θg from 40 cm (~12%) to 80 cm (~8%); and the RDI + CP treatment combination produced the lowest θg values (~8% throughout the soil profile). The effect of fruit load on mean θg within the soil profile was significant for trees in all of the treatment combinations (the probability estimated from the covariance analysis was 0.001); mean θg decreased with increases in fruit load (Fig. 6).

In 2004, differences in flowering and fruit set associated with treatment combinations applied in the previous year were not significant (Fig. 7).

Table 2. Effects of treatment combinations, sampling time and the interaction between treatment combinations and sampling time on individual fruit fresh weight (FW), individual fruit dry weight (DW) and relative dry matter (RDM), analysed by repeated measures ANOVA over time

Effects subject to ANOVA	2003			2004		
	FW (g)	DW (g)	RDM (%)	FW(g)	DW (g)	RDM (%)
Probability						
Treatment combinations	0.0001[1]	0.0856	0.0001	0.0001	0.0001	0.0001
Time	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Treatment × time	0.0017	0.9325	0.0001	0.0001	0.0001	0.0001
LSM for the treatment combinations						
FI + CP	58.61 a[2]	10.30	17.41 b	63.77 b	10.97 b	17.15 b
FI + WSR	60.83 a	10.40	17.06 c	67.88 a	11.58 a	16.87 c
RDI + CP	55.01 b	10.00	18.24 a	62.76 c	10.51 c	17.73 a

[1] Probability according to the repeated measures ANOVA over time. [2] Means followed by different letters in the same column are significantly different at 5% according to Tukey's test. LSM: least square means. FI: full irrigation. CP: commercial summer pruning. WSR: watersprout removal. RDI: no irrigation during stage II of fruit development.

No significant differences between treatment combinations were noted during the 2-year experiment in terms of fruit quality (Table 4).

Discussion

Regulated deficit irrigation during stage II of fruit development (RDI + CP) and watersprout removal in summer (FI + WSR) satisfactorily reduced vegetative growth compared to trees under commercial practices (FI + CP) (Fig. 1). The RDI + CP and FI + WSR treatments produced similar reductions in the percentage of PAR intercepted by the tree at the end of the two-year experiment. However, it was not possible to simulate the same seasonal patterns for the percentage of area covered by the tree using the RDI + CP and FI + WSR treatments. In 2003, the RDI + CP treatment showed a decrease in

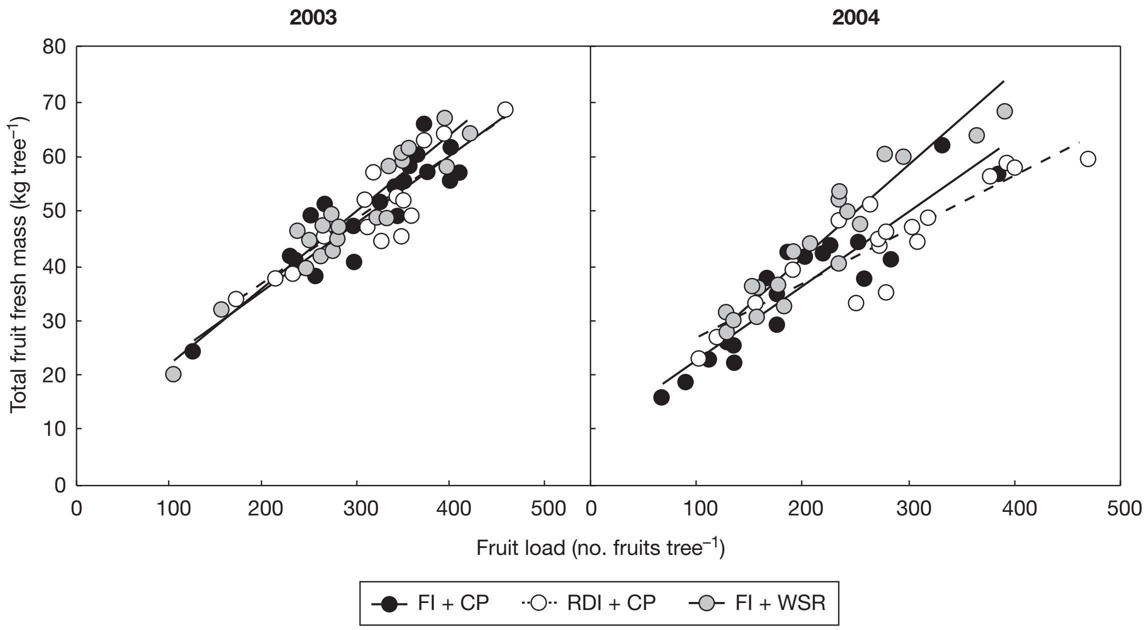

Figure 4. Relationships between fruit load and total fruit fresh mass at harvest. The relationships between fruit load and total fruit fresh mass were fitted to a simple linear regression. Each value represents one tree. FI: full irrigation. CP: commercial summer pruning. RDI: no irrigation during stage II of fruit development. WSR: watersprout removal.

Table 3. Probabilities for the test for heterogeneity of slopes in ANCOVA on total fruit fresh mass at harvest (yield) in each of the two experimental years. Means followed by different letters in the same column are significantly different at 5% using Tukey's test

Effects on yield	2003	2004
Probability		
Treatment	0.6657[1]	0.0702*
Covariable (no. fruits)	0.0001	0.0001
Heterogeneity of slopes (treatment × no. fruits)	0.5059	0.0002[2]
LSM for the treatment combinations (kg tree^{-1})		
FI + CP	49.71	40.67
FI + WSR	50.03	47.55
RDI + CP	51.34	40.06
Contrast of slopes between treatment combinations		
FI + CP *vs.* FI + WSR		0.8187
FI + CP *vs.* RDI + CP		0.0475
FI + WSR *vs.* RDI + CP		0.0485

[1] Probability according to covariance analysis (SAS, 1988). [2] When the heterogeneity of the slopes is significant, the assumptions for covariance analysis are not valid and the probability followed by an asterisk (*) is not relevant. LSM: least square means. FI: full irrigation. CP: commercial summer pruning. WSR: watersprout removal. RDI: no irrigation during stage II of fruit development.

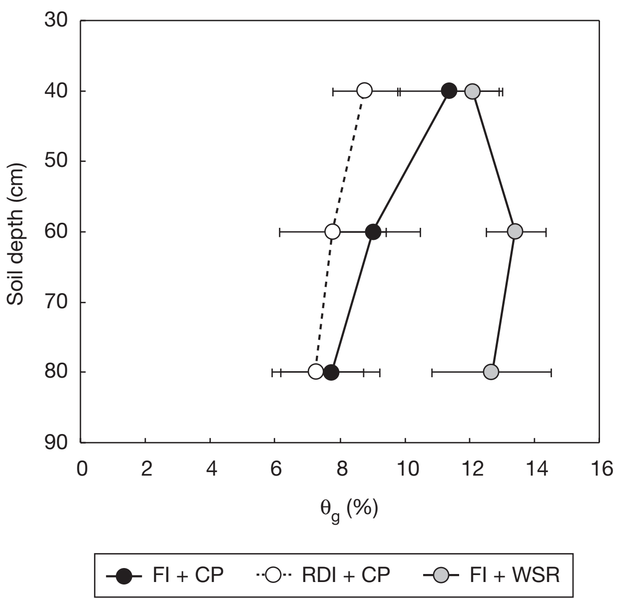

Figure 5. Gravimetric soil water content (θg) in the soil profile at harvest (2004). Each value is the mean for seven trees ± SE in the FI + CP and FI + WSR treatment combinations, and the mean for 14 trees ± SE in the RDI + CP treatment combination. FI: full irrigation. CP: commercial summer pruning. RDI: no irrigation during stage II of fruit development. WSR: watersprout removal.

the percentage of PAR intercepted as the productive cycle progressed, while the FI + WSR treatment caused an immediate reduction in the amount of PAR intercepted by the tree. In spite of this immediate reduction, the FI + WSR treatment showed an increase in the percentage of PAR interception in the period between summer pruning and harvest (Fig. 1). This increment may be explained by post-pruning regrowth (Myers, 1993). Similarly, the FI + WSR treatment may have stimulated shoot growth the following year (Marini, 1985), thus compensating the physiological balance with the root system (Chalmers *et al.*, 1981). Consequently, part of the difference in the observed percentage of PAR intercepted in 2003 between the FI + CP and FI + WSR treatments was reduced at the beginning of stage II in 2004 (Fig. 1). This compensation did not occur in the RDI + CP treatment and its trees exhibited a significant reduction in size at the beginning of the second experimental year (Fig. 1). For this reason, under the conditions of this experiment, reducing the amount of water applied during stage II seemed to be the most appropriate management practice for controlling tree vigour.

Comparing RDI and WSR as techniques for controlling vegetative vigour in summer, it is clear that RDI has the associated benefit of conserving water (Chalmers *et al.*, 1981; Mitchell and Chalmers, 1982).

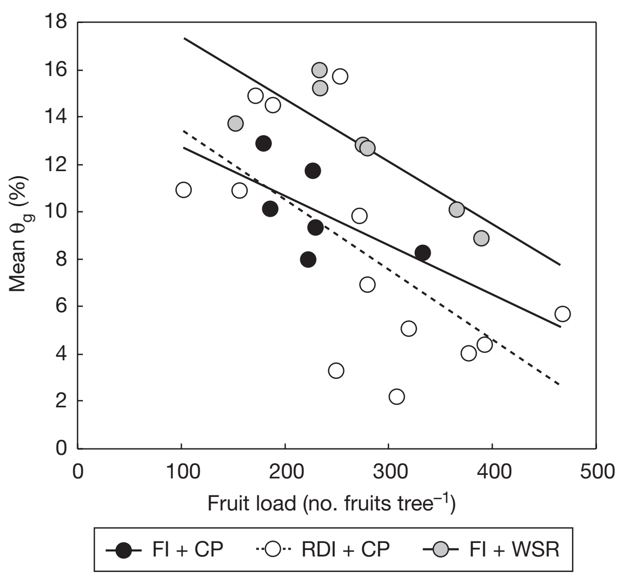

Figure 6. Relationship between fruit load and mean gravimetric soil water content (θg) within the soil profile at harvest (2004). Each value represents one tree. FI: full irrigation. CP: commercial summer pruning. RDI: no irrigation during stage II of fruit development. WSR: watersprout removal.

Table 4. Effects of treatment combinations on fruit quality, analyzed by ANOVA

Year	Effects subject to ANOVA	FF (N)	SSC (°Brix)	TA (g malic acid L^{-1})	Fruit cheek colour	
					Less coloured (Hue angle)	More coloured (Hue angle)
2003	*Probability*	0.2952[1]	0.4340	0.3487	0.7352	0.0703
	LSM for the treatment combinations					
	FI + CP	2.01	12.45	9.67	54.04	34.15
	RDI + CP	2.06	12.48	10.53	53.94	36.31
	FI + WSR	1.88	12.10	10.09	54.66	31.39
2004	*Probability*	0.4720	0.5147	0.7793	—	—
	LSM for the treatment combinations					
	FI + CP	7.13	12.74	12.55	—	—
	RDI + CP	6.29	13.02	12.23	—	—
	FI + WSR	6.64	12.34	12.30	—	—

[1] Probability according to ANOVA analysis. —: no data available. FF: flesh firmness. SSC: soluble solid content. TA: titratable acidity. LSM: least square means. FI: full irrigation. CP: commercial summer pruning. RDI: no irrigation during stage II of fruit developmen. WSR: watersprout removal.

Trees subjected to the RDI + CP treatment showed reductions of 15.0-20.0% in the irrigation water during the growing season, as compared to trees following the FI + CP and FI + WSR treatments. This reduction in irrigation water should be taken into account in water-limited areas, such as the Mediterranean. Moreover, RDI also had the associated benefit of reducing the labour cost of pruning (García *et al.*, 2004): in 2004, RDI + CP trees did not require commercial summer pruning. Nevertheless, under the conditions of our experiment, the RDI technique was accompanied by a limitation in fruit growth capacity (Table 2, Fig. 3). This limitation was more evident in 2004 than in 2003 (Table 2, Fig. 3); in 2004, trees in the RDI + CP treatment showed a reduction in total fruit fresh mass compared to the FI + CP and FI + WSR treatments, but only at high crop loads (Table 3, Fig. 4). On the other hand, the FI + WSR treatment was associated with the highest rates of fruit growth (Table 2, Fig. 3).

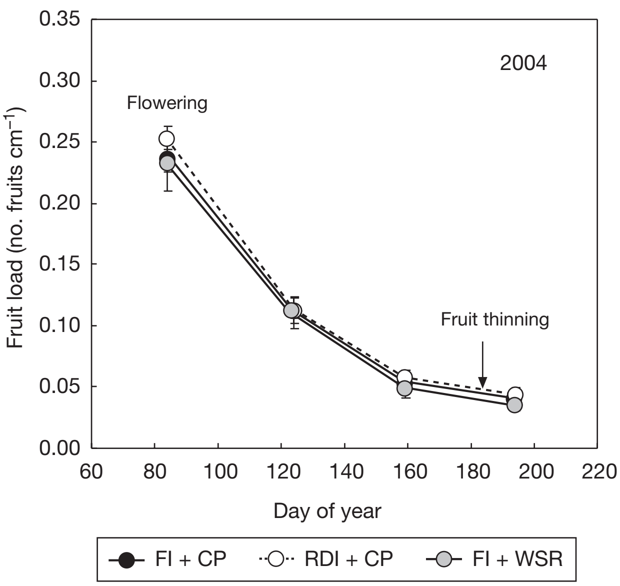

Figure 7. Seasonal variations in crop load per unit branch length in response to tratment combinations applied in the previous season. Each value is the mean for 21 trees ± SE. FI: full irrigation. CP: commercial summer pruning. RDI: no irrigation during stage II of fruit development; WSR: watersprout removal.

The observed reduction in fruit growth capacity and total crop yield after RDI during stage II was not surprising as other authors have reported similar negative effects (Goldhamer *et al.*, 2002; Girona *et al.*, 2003). Taking into account our results and previous research reporting negative long-term effects following deficit irrigation (Goldhamer and Viveros, 2000; Ebel *et al.*, 2001; Alegre *et al.*, 2002; Girona *et al.*, 2005), it seems appropriate to make a distinction between the effects of water stress on fruit growth in the current growing season and the carry-over effects of water stress. The effects of water stress on fruit growth during the current growing season may be related with factors impairing fruit growth recovery after re-establishing full irrigation. One of such factors is soil depth (Marsal *et al.*, 2004); when soil depth was about 0.5-2.0 m, fruit growth fully recovered after re-establishing full irrigation. However, when soil depth exceeded 2.0 m (as in this experiment) fruit growth did not achieve its potential capacity. Another factor influencing fruit growth recovery could be crop load. Tree water status at high crop loads has been reported to be more sensitive to irrigation restrictions than at low crop loads (Marsal *et al.*, 2006). In our study, there was a significant negative correlation between fruit load and θg (Fig. 6), which could have reduced the amount of water available for fruit growth at high fruit loads (Table 3, Fig. 4). This result indicates that the RDI + CP treatment could have reduced θg to below the threshold required for optimum fruit growth. Regarding the potential long-term effects of water stress, Marsal *et al.* (2006) proposed three main mechanisms explaining the negative effects of water stress on fruit growth in subsequent years: bud differentiation, carbon reservoir, and tree size. In peach trees, however, limitations on bud differentiation and the carbon reservoir do not affect subsequent crop yield if an appropriate commercial crop is achieved (Marsal *et al.*, 2006; Lopez *et al.*, 2007). This was the case in our experiment: after one year of RDI, the RDI + CP treatment did not show any reduction in the cropping level of the trees (Fig. 7). However, the reduction in tree size may have played a significant role in fruit growth limitation during the second experimental year. Reductions in shoot growth during early shoot development (stage I) have been reported to have an impact on the development of leaves close to fruits and to reduce the carbon supply to fruits during the later period of high demand (Girona *et al.*, 2004).

On the other hand, the effects of summer pruning on fruit growth capacity are highly varied (Chalmers *et al.*, 1981; Marini, 1985; Rom and Ferree, 1985; Myers, 1993; Kappel and Bouthillier, 1995; Francisconi *et al.*, 1996; Bussi *et al.*, 2005; Lopez *et al.*, 2006). From these studies, it is clear that summer pruning should maintain total tree carbohydrate acquisition in order to ensure optimum fruit growth. However, the effect of soil water on fruit growth following summer pruning has yet to be adequately studied. Under the conditions of this experiment, tree crown reduction in the FI + WSR treatment tended to improve tree water status (Table 1) compared to the FI + CP treatment (Table 1). Consequently, more water was available in the soil profile in the FI + WSR treatment (Fig. 5) and a certain benefit was observed in terms of fruit growth (Table 2, Fig. 3) (Li *et al.*, 2003).

Reducing the amount of water available during stage II of fruit development and summer watersprout removal effectively reduced excessive vegetative growth. However, the effects associated with reductions in vegetative growth following these two techniques were very different. Under the conditions of this experiment, significant differences were observed between the two techniques with respect to the dynamics of the areas covered by the trees (Fig. 1). Although these differences were not accompanied by significant changes in parameters related with improvements in light interception by trees, such as flowering (Fig. 7) and fruit quality (Table 4), the mechanisms responsible for vegetative growth reduction significantly affected both the water status of the tree (Table 1) and soil water content (Fig. 5). These differences may have produced opposing responses between the two treatments (RDI + CP and FI + WSR) with respect to the amount of water available for fruit growth. While the RDI + CP technique may have reduced θg to below the threshold required for optimum fruit growth, it seems that the lower water consumption and improved water status associated with FI + WSR may have benefited fruit growth. Numerous interacting factors were associated with the negative responses of soil water content to moderate water stress. These factors included soil depth and crop load. From this research we can conclude that RDI should be applied taking into account specific orchard circumstances and adjusted to the productive cycle based on accurate water stress threshold measurements. Further research is needed to establish water stress thresholds and thereby ensure fully successful implementation of RDI techniques and reductions in agricultural water use that do not affect crop yields, which is the fundamental objective of RDI.

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