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ORIGINAL PAPER

Using midday stem water potential for scheduling deficit irrigation in mid–late maturing peach trees under Mediterranean conditions

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Abstract Irrigation techniques that reduce water applications are increasingly applied in areas with scarce water resources. In this study, the effect of two regulated deficit irrigation (RDI) strategies on peach [*Prunus persica* (L.) Batsch cv. "Catherine"] performance was studied over three growing seasons. The experimental site was located in Murcia (SE Spain), a Mediterranean region. Two RDI strategies (restricting water applications at stage II of fruit development and postharvest) based on stem water potential (Ψ_s) thresholds (−1.5 and −1.8 MPa during fruit growth and −1.5 and −2.0 MPa during postharvest) were compared to a fully irrigated control. Soil water content (θ_v), Ψ_s, gas exchange parameters, vegetative growth, crop load, yield and fruit quality were determined. RDI treatments showed significantly lower values of θ_v and Ψ_s than control trees when irrigation water was restricted, causing reductions in stomatal conductance and photosynthesis rates. Vegetative growth was reduced by RDI, as lower shoot lengths and pruning weights were observed under those treatments when compared to control. However, fruit size and yield were unaffected, and fruit quality was slightly improved by RDI. Water savings from 43 to 65 % were achieved depending on the year and the RDI strategy, and no negative carryover effect was detected during the study period. In conclusion, RDI strategies using Ψ_s thresholds for scheduling irrigation in mid–late maturing peach trees under Mediterranean conditions are viable options to save water without compromising yield and even improving fruit quality.

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Introduction

Agriculture is the primary user of water worldwide, reaching 70–80 % of total water consumption in arid and semiarid regions (Fereres and Soriano 2007). The pressure on water resources is increased by competition between agriculture, industry and population. This situation promotes agricultural water conservation, especially in orchards equipped with drip irrigation systems.

Spain is worldwide the second largest producer of peach [*Prunus persica* (L.) Batsch]. Peach tree plantations are located in the Mediterranean area, and Murcia (SE Spain) is the third main peach production area in the country, producing 249,500 t year^{-1}, approximately 19 % of the Spanish production (MAGRAMA 2015).

Due to the increasing limitation of irrigation water for horticultural crops in Mediterranean areas, there is an increasing risk of losing irrigated land. Reducing applied water during certain periods of the year could improve water use efficiency and conservation. The focus would be not only to achieve above average production or to control vegetative growth but to reduce water use even while risking a slight reduction in production (Girona et al. 2003).

Precise tools for assessing crop water requirements are needed in order to reduce irrigation water use without compromising crop yield and quality. One of the most promising techniques to achieve this objective is regulated deficit irrigation (RDI), which was first developed in Australian peach orchards (Chalmers et al. 1981). This technique consists of applying less irrigation water than crop evapotranspiration (ET_c) during certain periods of the crop cycle when yield and quality would be hardly affected, and restoring full irrigation for the rest of the cycle. While the major concept in RDI was to control excessive vegetative growth and enhance fruit growth (Chalmers et al. 1981), additional advantages such as improvement in fruit quality and taste have also been described (Crisosto et al. 1994; López et al. 2011).

RDI has typically been applied when reproductive growth is relatively slow and when vegetative growth and other plant processes may be affected, thus improving fruit quality (Ruiz-Sánchez et al. 2010). RDI has been successfully employed in many fruit crops including citrus (Goldhamer and Salinas 2000; González-Altozano and Castel 2000), peach (Girona et al. 2003; Buendía et al. 2008; López et al. 2008) and other species (Ruiz-Sánchez et al. 2010).

In most of the research on peach response to RDI, water restriction was applied during stages I and II of fruit development (initial growth and pit hardening, respectively), as well as at postharvest, whereas full irrigation was applied at stage III when deficit irrigation might provoke yield reductions due to lower fruit weights (Abrisqueta et al. 2010).

The water balance method (Allen et al. 1998) is the established technique for estimating full irrigation requirements. However, when dealing with RDI, indicators that account for plant water status must be used. Approaches such as trunk diameter fluctuations (TDF) (Fernández and Cuevas 2010; Conejero et al. 2011), sap flow (Conejero et al. 2007) and stem water potential (Ψ_s) (Shackel et al. 2010) have been studied. Sap flow and TDF have been reported less reliable than Ψ_s (Moriana et al. 2003; Intrigliolo and Castel 2006). At a commercial level, the use of leaf and stem water potential is considered more practical (Naor and Cohen 2003; Bonet et al. 2010; Moriana et al. 2010). The use of sap flow sensors in commercial orchards poses some inconvenience related to underestimation of expected tree transpiration and the need to increase the number of gauges making the system too expensive for non-scientific purposes. In addition, when direct calibration cannot be performed, such as in commercial applications, relative transpiration values between control and RDI trees should be used (Ballester et al. 2013). In the case of TDF measurements, their main drawback is difficulty in interpretation and difficulty in application in irrigation scheduling (Fernández and Cuevas 2010).

Several studies proved the feasibility of using threshold values of plant parameters as irrigation triggers (Besset et al. 2001; Goldhamer and Fereres 2004). Girona et al. (2006) proved that leaf water potential thresholds could be successfully used for scheduling irrigation in vineyards and a similar approach has been suggested for peach orchards (Ghrab et al. 2013).

The aims of the current study were to (1) apply a methodology based on the protocol proposed by Goldhamer and Fereres (2001) for scheduling peach orchard irrigation using Ψ_s thresholds as stress indicators for triggering irrigation and (2) assess the effects of RDI on peach tree physiology, vegetative growth, yield and fruit quality, as well as water savings, when compared to an over-irrigated control treatment.

Materials and methods

Site description and plant material

The experiment was performed over three consecutive years (2008–2010) in a 0.5 ha plot of a commercial orchard located in Mula Valley, Murcia, SE Spain (37°55′N, 1°25′W, 360 m above sea level). The soil at the site is calcareous, stony, with a sandy-loam texture, low organic matter content and approximate field capacity of 0.25 m^3 m^{-3}. The climate of the region is semiarid Mediterranean with hot and dry summers and low rainfall. Annual reference crop evapotranspiration (ET_0) and rainfall were, respectively, 1055 and 318 mm in the first year of the experiment (2008), 1064 and 568 mm in 2009 and 991 and 388 mm in 2010.

Plant material consisted of peach trees [*Prunus persica* (L.) Batsch cv. "Catherine"] grafted on GF-677 rootstock and planted in 1999. At the beginning of the experiment, peach trees had a similar trunk cross-sectional area (TCSA), approximately 130 cm^2. Tree spacings were 4 m × 6 m. Hand thinning was used to space fruitlets 25–30 cm along the fruit-bearing shoots in order to achieve a commercial crop load, except in 2009 when fruitlets were spaced 10–15 cm since that year fruit production was oriented to the canned food industry. Pest control was that commonly used by the growers in the region. All treatments received the same fertilization ($N–P_2O_5–K_2O$), applied through the drip irrigation system (275–125–200 kg ha^{-1} $year^{-1}$) over the study period.

Irrigation treatments and experimental design

Irrigation water was supplied through a drip irrigation system, one pipeline for each row, with three emitters per tree, each delivering 4 L h^{-1}. The irrigation water was considered of good quality with a very low electrical conductivity (0.6 dS m^{-1}).

Crop irrigation requirements were scheduled weekly according to daily ET_0, calculated using the Penman–Monteith equation (Allen et al. 1998), and a local crop factor based on the time of the year, used commercially in this region. Monthly average values of K_c employed for the control treatment from April to October were 0.73, 0.83, 0.94, 0.96, 0.39, 0.39 and 0.39, respectively. A total of 192

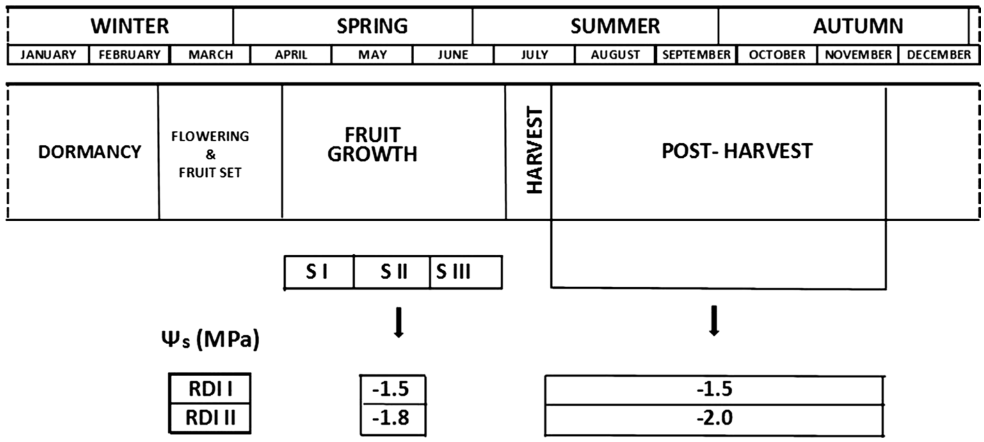

Fig. 1 Regulated deficit irrigation (RDI I: moderate deficit, RDI II: severe deficit) strategies based on threshold values for midday stem water potential (Ψ_s), applied in stage II (S II) of fruit growth and postharvest during the 3 years of the experiment

trees were used in the study. The experiment was laid out in complete randomized blocks with four replications (16 trees each). The four central trees were used for measurements, and the other 12 trees acted as a border.

Three irrigation treatments were applied based on peach tree water status (Fig. 1): Control plants (treatment C) were daily irrigated above the estimated ET_c in order to obtain non-limiting soil water conditions (approximately 120 % ET_c in 3 years of experiments), and two RDI strategies that consisted of a full irrigation at 100 % ET_c during critical periods and water restrictions during the non-critical periods of crop development (stage II of fruit growth and post-harvest period). The RDI treatments were:

(a) RDI I (moderate deficit) plants were irrigated to maintain Ψ_s values close to −1.5 MPa during stage II of fruit growth and postharvest.
(b) RDI II (severe deficit) plants were irrigated to maintain Ψ_s values close to −1.8 MPa at stage II of fruit growth and −2.0 MPa at postharvest.

The threshold values were selected based on local experience taking into account experimental studies in mid–late maturing peach cultivars grown in the Mediterranean area, either for fruit growth stage (Girona et al. 2005a, b) or for the postharvest period (Dichio et al. 2007). Lampinen et al. (2001) employed a similar protocol for deficit irrigation in prune. Moreover, Rahmati et al. (2015) reported that Ψ_s values more negative than −1.5 MPa would cause a negative C balance in peach.

The irrigation rate was decreased by 10 % when stem water potential on at least two out of three consecutive days was equal to or less negative than the threshold value. The irrigation rate was increased by 10 % when the stem water potential was more negative than the threshold value on at least two out of three consecutive days. This irrigation protocol was based on that proposed by Goldhamer and Fereres (2001) for mature trees grown under high-frequency irrigation.

Irrigation was automatically controlled by a head unit programmer, and the amounts of water applied for each irrigation treatment were measured with in-line flowmeters placed in each experimental plot.

Field and laboratory determinations

Climate data

Climate data were recorded by an automatic weather station placed within the experimental orchard. Air temperature (maximum, minimum and average), solar radiation, air relative humidity, rainfall and wind speed 2.5 m above the soil surface were collected every 15 min. These data were used for calculating ET_0 and crop water requirements.

Soil water content

The volumetric soil water content (θ_v, $m^3\ m^{-3}$) of the top 0.2 m of the soil profile was measured by time-domain reflectometry (TDR) using a Tektronix device (Model 1502C, Tektronix Inc., OR), as described by Moreno et al. (1996). The θ_v from 0.2 m down to a maximum depth of 1.0 m was measured every 0.1 m using a neutron probe (Model 4300, Troxler Electronic Laboratories Inc., NC), in access tubes installed 1.0 m from the trees and adjacent to the emitters. The probes were placed 0.2 m from the emitter and next to the TDR rods. Measurements using one neutron probe and TDR per experimental plot (three replications per treatment) were taken in the morning, every 7–15 days, during the experimental period.

Stem water potential

Midday stem water potential (Ψ_s) was measured using a pressure chamber (Soil Moisture Equip. Corp, model 3000, Santa Barbara, CA, USA) following the procedures described by Turner (1981). Measurements were performed on mature leaves (one per tree) from the north face of the trunk, in the four central trees of each experimental plot (16 measurements per treatment). Leaves were enclosed in plastic bags covered with aluminum foil at least two hours prior to the measurements, carried out every 3 days between 12:00 and 13:00 h solar time.

Water stress integral

The water stress integral (MPa days) was calculated from the Ψ_s data in order to evaluate the intensity of water stress, according to the following equation (Myers 1988):

$$S_\Psi = \left| \sum (\psi_m - c)n \right|$$

where Ψ_m is the average Ψ_s for each time interval, c is the value of the maximum (least negative) Ψ_s in all seasons (−0.4 MPa) and n is the number of days in the interval.

Gas exchange parameters

Net photosynthesis (P_n) and stomatal conductance (g_s) were measured at solar midday, in one fully expanded sun-facing leaf in the four central trees of each experimental plot per treatment (16 measurements per treatment), on the same days that stem water potential was recorded, using a field-portable photosynthesis system (LI-6400, Li-Cor, Lincoln, NE, USA) equipped with a LI-6400-01 CO_2 injector. The CO_2 concentration in the cuvette was maintained at 390 µmol mol^{-1} (approximately the ambient CO_2 concentration).

Vegetative growth

Trunk diameter was measured annually at the end of each growing season in 16 trees per treatment with a sliding caliper, 0.20 m above the soil surface, and used to estimate trunk cross-sectional area (TCSA). Pruning weight was recorded for 16 trees per treatment (four per replication) at winter pruning. Shoot length values were collected every 7–10 days by measuring the lengths of 10 randomly selected shoots in the four inner trees of each experimental plot per treatment.

Fruit growth and yield

Fruit diameter was measured perpendicularly to the fruit suture on 160 fruits per treatment (40 fruits per replication) every 7–10 days. Each date, 10 fruits per tree were randomly selected on the four inner trees per experimental plot and their diameters measured using a digital caliper (Powerfix model Nr Z22855F, Milomex Ltd, Bedfordshire, UK).

Fruits from each tree were individually harvested on July in two or three commercial picks, depending on market demands. The number of fruits per tree was obtained by counting the fruits in the four inner trees (16 trees per treatment).

Fruit quality

At harvest, 100 fruits per treatment (25 fruits per experimental plot) were randomly selected for quality assessment. Chemical analyses were performed according to Artés et al. (1993). Fruit firmness was evaluated using a Durofel penetrometer DFT100 (Agro-Technologie S.A., Paris, France). Juice was extracted from combined samples of longitudinal unpeeled slices (four independent determinations per treatment). Total soluble solids concentration (SSC) was determined with a hand refractometer (Atago, Co., Japan); values were expressed as ºBrix. Titratable acidity (TA) was measured by titration of 5 mL of juice with 0.1 mol L^{-1} NaOH to pH 8.1 using an automatic titration system and expressed as g malic acid L^{-1}. pH was measured using a pH meter (Crison, Barcelona, Spain). The maturity index (MI), which affects the perception of taste (sweetness and acidity), was calculated as the ratio of SSC to TA.

Statistical analysis

Statistical analysis was performed as a weighted analysis of variance (ANOVA; statistical software IBM SPSS Statistics version 21 for Windows). The Shapiro–Wilk test was used to evaluate the normality of the data. Tukey's HSD test was used for mean separation. Linear regression was used for determining the relationship between the amounts of water applied and the pruning weight. Unless otherwise stated, the significance level was $p < 0.05$.

Results

Reference ET_0 over the growing season (full bloom 22 March to end of October) was quite similar from year to year, ranging between 812 mm in 2010 and 842 mm in 2009. Rainfall was more variable during the experimental period, from 188 mm during the 2010 growing season to 372 mm in 2009. Rainfall was relatively important during early spring (end of March and April) and postharvest, although more than 50 mm were registered during stage II of fruit development in 2008 (Fig. 2). During the experimental period, rainfall accounted for an average of 31 % of total ET_0 over the growing season.

Soil water content from 0 to 1 m depth (Fig. 3b) was nearly constant over the experimental period for the C treatment, with values close to field capacity. In the RDI

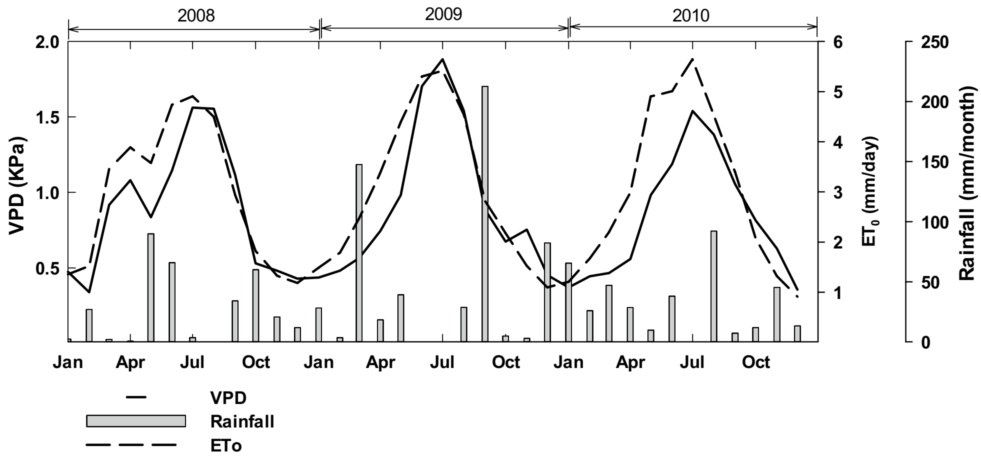

Fig. 2 Reference evapotranspiration (ET_0), rainfall (mm) and daily vapor pressure deficit (VPD in kPa) in Fuente Librilla. Monthly values from data collected during the 3 years of the experiment

treatments, θ_v decreased during the stage II of fruit development (down to 0.19 m^3 m^{-3} under RDI I and 0.18 m^3 m^{-3} for RDI II) and recovered in stage III, when full irrigation was restored. During the postharvest period, the θ_v decreased as a result of deficit irrigation, reaching significantly lower values in RDI I (0.17–0.18 m^3 m^{-3}) and RDI II (0.16 m^3 m^{-3}) as compared to the C treatment (Fig. 3b).

Clear differences in average Ψ_s values for each irrigation treatment were evident (Fig. 4). In the early part of the season, Ψ_s below the thresholds for RDI I and RDI II trees was rarely observed. Consequently, little water was applied to the RDI trees during this stage (Fig. 3a). However, RDI trees presented significantly lower Ψ_s values than C trees during stage II of fruit development, except in 2010 (Table 1). When full irrigation was restored in stage III, Ψ_s was similar for the three treatments.

During postharvest, Ψ_s in RDI treatments reached the threshold values in 2008 and 2009 (Fig. 4). Differences in Ψ_s between the RDI treatments were significant on certain dates (Table 1). However, the lower threshold for irrigation triggering in RDI II (−2.0 MPa) was never reached in 2010 (Fig. 4) which was a year characterized by a more homogeneous distribution of rainfall over the growing season and lower evaporative demand compared with 2009.

The amounts of water applied during the first year of the experiment (2008) were 962, 454 and 330 mm for C, RDI I and RDI II, respectively (Fig. 3a). These amounts were reduced in 2009 and 2010 and were more similar for the two RDI treatments, namely 849, 289 and 247 mm for C, RDI I and RDI II, respectively, in 2009; and 710, 213 and 206 mm for C, RDI I and RDI II, respectively, in 2010. These differences were due to climate conditions that did not cause Ψ_s values to be lower than the scheduled thresholds in both RDI periods, and thus, irrigation was restricted and hardly applied during postharvest in 2010 (Fig. 3a). As a consequence, when compared to ET_c, water reductions of 26–45 % in 2008, 49–55 % in 2009 and 64–65 % in 2010 were achieved for RDI I and RDI II treatments, respectively.

Overall for the whole season, S_Ψ values reflected the significant differences between treatments. RDI II showed the highest values of water stress integral (Fig. 5), but was only significantly higher than RDI I in 2008. For stages of fruit development, water stress integral values reflected the differences in irrigation treatments, as observed by Ψ_s. Thus, during stage II of fruit development, significantly greater S_Ψ values were detected for RDI I and RDI II treatments when compared to C (Table 2). However, these differences were not maintained in 2010, when a low evaporative demand caused the values of S_Ψ to be similar among treatments. However, at postharvest, RDI II reflected the highest S_Ψ values, showing significant differences from RDI I only in 2008 (Table 2), and always with respect to the control treatment.

Gas exchange parameters showed a similar trend over the growing season as that of Ψ_s. However, significant differences between treatments were observed less often than for Ψ_s. Significant reductions in net photosynthesis rate (P_n, Fig. 6a) and leaf stomatal conductance (g_s, Fig. 6b) for the RDI treatments compared to C were observed at postharvest and in one date during the stage II of fruit development for the P_n and two dates for g_s values in the RDI treatments being, approximately, one-third of those measured in C trees.

Vegetative growth was restricted by RDI when compared to C. Shoot length of RDI trees was significantly lower than that observed for C trees (Fig. 7a), although no differences were observed between both RDI treatments by the end of the season. In addition, TCSA was similar for the three treatments considered on the first year of

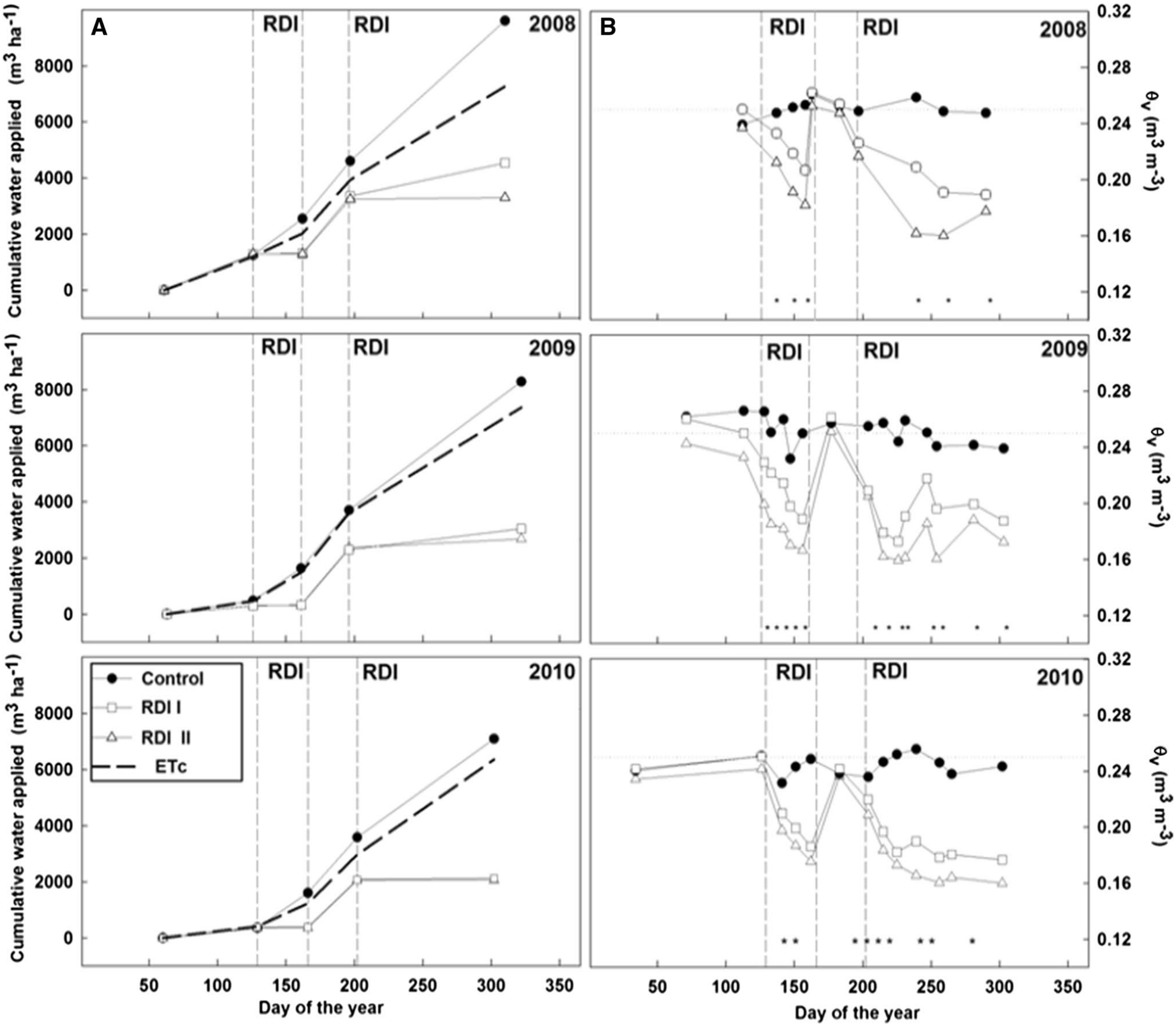

Fig. 3 Seasonal patterns of **a** cumulative applied water and **b** volumetric soil water content down to 1 m depth (θ_v), in C (*closed circles*), RDI I (*open squares*) and RDI II (*open triangles*) treatments for the 3 years of the experiment. *Each data point* is the mean of three values. *Asterisks* indicate significant differences between treatments ($p < 0.05$). The interval between *vertical lines*, from *left to right*, represents the beginning of stages II and III of fruit growth and postharvest. *Horizontal lines* represent field capacity

the experiment (Table 3). However, this parameter was significantly lower for RDI trees in 2009 and 2010. Pruning weight was significantly higher in the C trees than in those subjected to RDI (Fig. 8a). A linear correlation between pruning weight and the amount of water applied was detected (Fig. 8b), with a significant determination coefficient ($r^2 = 0.81$, $p < 0.01$). On the contrary, fruit development was mainly unaffected by water restrictions. Fruit growth, expressed as fruit diameter, was very similar among treatments (Fig. 7b). This was true as well for fruit set (Table 3), despite of a higher flower density in the RDI treatment in 2009 and 2010. Crop load and total yield were similar among treatments although highly variable between years (Table 4). Furthermore, no differences between treatments were observed for fruit distribution into commercial categories (data not shown), as observed in the average fruit weights (Table 4).

The fact that similar yields were obtained for the three treatments studied caused irrigation water productivity (IWP) values to be higher under RDI treatments when compared to the control (Table 4). Therefore, water savings were registered for RDI treatments, being greater under RDI II than RDI I (Table 4). When compared to control and depending on the year, RDI I resulted in between 38 and 67 % water savings for the whole season, whereas RDI II saved between 55 and 68 %.

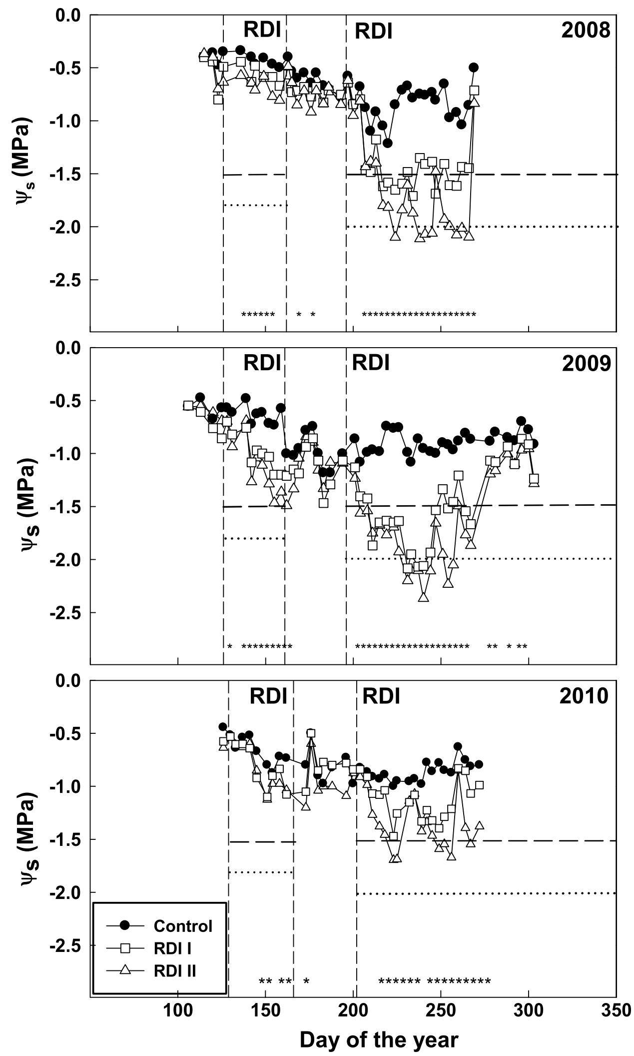

Fig. 4 Midday stem water potential values for each irrigation treatment for the 3 years of the experiment: C (*closed circles*), RDI I (*open squares*) and RDI II (*open triangles*) plants. *Each data point* is the mean of four values (average of four replications per treatment). *Asterisks* indicate significant differences between treatments ($p < 0.05$). The interval between *vertical lines*, from *left to right*, represents the beginning of stages II and III of fruit growth and postharvest. *Horizontal lines* represent threshold values in each phenological stage for both RDI treatments

Fruit quality parameters reflected certain differences between treatments (Table 5). Fruit firmness was unaffected by irrigation treatments, and titratable acidity was only affected in 2010 since pH showed a tendency to reach lower values under RDI treatments, mainly in the two first years of the experiment. On the contrary, SSC was significantly higher under RDI when compared to C in the last 2 years of the experiment. This caused a greater MI in RDI than in C, except for 2009 (Table 5).

Discussion

During pit hardening (Stage II), peach fruit growth is understood to not be very sensitive to water stress (Chalmers et al. 1981). In this study, the effects of two different RDI treatments on peach fruit growth were negligible during the 3 years of the experiment (Fig. 7b). The RDI strategies were applied at stage II of fruit development and at postharvest based on Ψ_s thresholds, as proposed by Girona et al. (2006), since this indicator of plant water status is very sensitive to water deprivation (Remorini and Massai 2003).

The use of Ψ_s for irrigation scheduling has progressed in recent years, especially for managing RDI in fruit trees and vines (Girona et al. 2006; Shackel et al. 2010). This indicator provides more site-specific information than the water balance method, and therefore, it can account for spatial variability within the field (Girona et al. 2006). These measurements should be carried out frequently and in different sites within the orchard in order to schedule irrigation precisely (Goldhamer and Fereres 2001). We performed midday stem water potential measurements each 3 days on 48 trees (16 per treatment), accounting for an area of 1152 m^2 (25 % of the surface of the orchard). We consider that this was sufficient for assessing temporal and spatial scale tree water status and to precisely schedule deficit irrigation in the orchard.

The increasing evaporative demand during postharvest caused the reaching of Ψ_s thresholds, and thus, irrigation was applied accordingly (Fig. 3). However, in the last year

Table 1 Average midday stem water potential (MPa) in different stages of fruit growth for the 3 years of the experiment

	Stage I	Stage II	Stage III	Postharvest
2008				
C	−0.40a	−0.43a	−0.60a	−0.85a
RDI I	−0.53a	−0.57b	−0.71ab	−1.40b
RDI II	−0.53a	−0.68b	−0.74b	−1.69c
2009				
C	−0.57a	−0.62a	−0.99a	−0.90a
RDI I	−0.64a	−0.96b	−1.14a	−1.48b
RDI II	−0.58a	−1.05b	−1.14a	−1.66b
2010				
C	−0.45a	−0.67a	−0.82a	−0.86a
RDI I	−0.58a	−0.80a	−0.80a	−1.13b
RDI II	−0.64a	−0.82a	−0.97a	−1.36c

Each data point is the mean of all values in the corresponding stage. Different letters next to a value in each year indicate significant differences between treatments according to Tukey's multiple range test ($p < 0.05$)

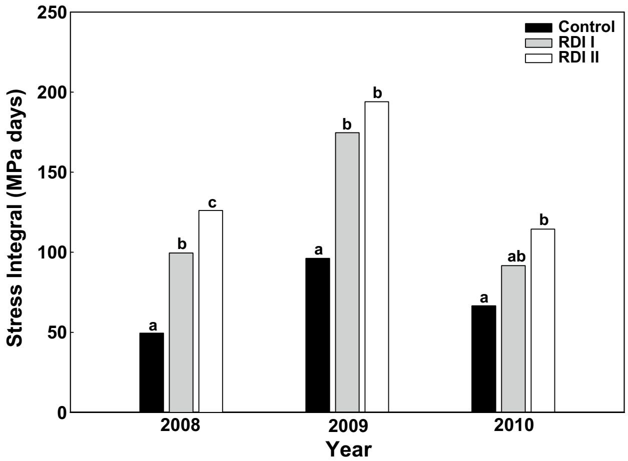

Fig. 5 Stress integral for each irrigation treatment, control (*black bars*), RDI I (*gray bars*) and RDI II (*white bars*) for the 3 years of the experiment. *Different letters* on *top* of *bars* indicate significant differences according to Tukey's multiple range test ($p < 0.05$)

Table 2 Stress integral average values (MPa days) in different stages during the 3 years of the experiment calculated with the midday stem water potential of Fig. 4

	Stage I	Stage II	Stage III	Postharvest
2008				
C	0.7a	2.7a	10.7a	36.4a
RDI I	2.2a	8.2b	15.0a	76.8b
RDI II	1.8a	12.1c	16.5a	98.5c
2009				
C	4.5a	11.1a	22.6a	58.9a
RDI I	6.8a	23.7b	28.0a	118.2b
RDI II	5.1a	28.1b	27.5a	135.8b
2010				
C	0.4a	12.6a	16.6a	36.9a
RDI I	0.6a	18.3a	19.8a	55.0b
RDI II	0.7a	19.0a	25.9a	71.0b

Each data point is the mean of all values in the corresponding stage. Different letters next to a value in each year indicate significant differences according to Tukey's multiple range test ($p < 0.05$)

of the experiment (2010), the Ψ_s threshold for triggering irrigation in the RDI II treatment was never achieved and irrigation water was not applied (only the minimum amount of water was provided to supply fertilizer). The lowest Ψ_s values measured for C, RDI I and RDI II trees were, respectively, −0.9, −2.0 and −2.4 MPa, depending on the year, although they were always reached at postharvest. These reflect conditions of the absence of water stress, moderate and severe water stress, respectively (Remorini and Massai 2003), and followed the same trend as soil water content in the different treatments.

Tree functioning and gas exchange attributes were affected by water deprivation, as lower P_n and g_s values were observed under RDI treatments, mainly in the postharvest period (Fig. 6). This indicates that peach trees regulated their transpiration when subjected to water constraints (Girona et al. 1993; Ruiz-Sánchez et al. 2010), which is a common response of cultivated plants grown in Mediterranean climates (Schulze et al. 1972; Tenhunen et al. 1982; Pereira et al. 1986). A delay in the recovery of these functions after the stage II of fruit development was observed when full irrigation was restored, as previously reported for other species (Torrecillas et al. 1999; Romero et al. 2004). This progressive recovery after rewatering can be considered a mechanism for maintaining leaf productivity and promoting leaf rehydration (Torrecillas et al. 1999).

Vegetative growth, either the dynamics (shoot elongation) or the integral (TCSA and pruning weight) for the whole growing season, was significantly reduced by irrigation withholding during stage II and postharvest, when

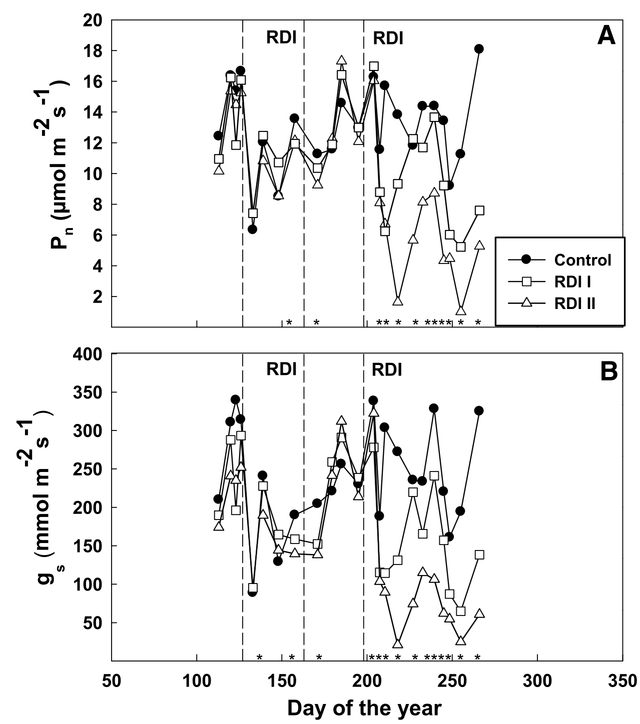

Fig. 6 Net photosynthesis (P_n, **a**) and stomatal conductance (g_s, **b**) values averaged for the three studied growing seasons in the control, C (*closed circles*), RDI I (*open squares*) and RDI II (*open triangles*) plants. *Each data point* is the mean of four values (average of four replications per treatment). *Asterisks* indicate significant differences between treatments ($p < 0.05$). The interval between *vertical lines*, from *left to right*, represents the beginning of stages II and III of fruit growth and postharvest

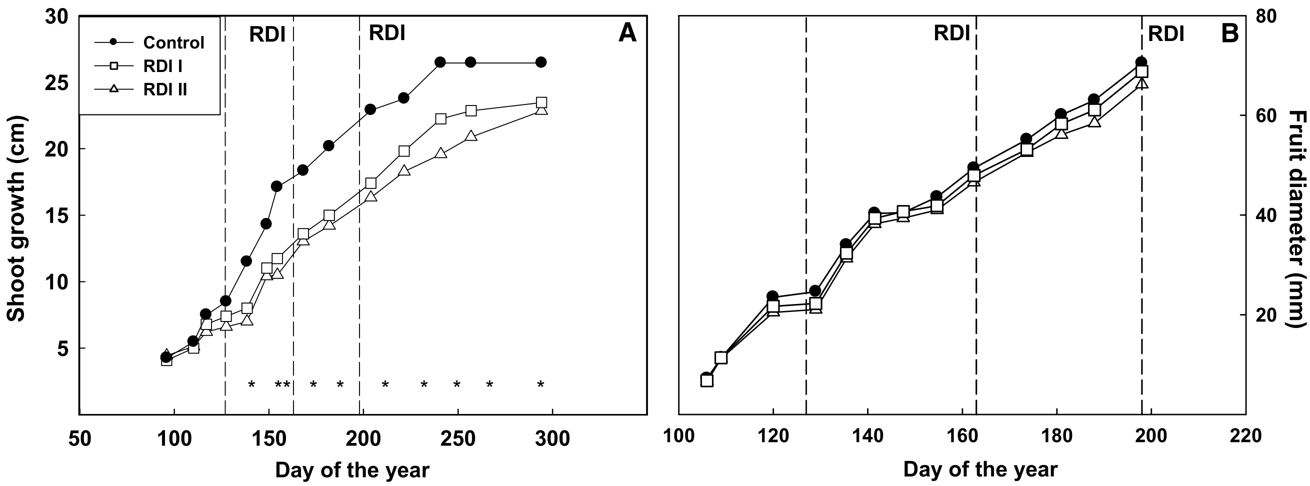

Fig. 7 Shoot growth (**a**, cm) and fruit diameter (**b**, mm) evolution in the control, C (*closed circles*), RDI I (*open squares*) and RDI II (*open triangles*) trees for the 3 years of the experiment. The interval between *vertical lines*, from *left to right*, represents the beginning of stages II and III of fruit growth and postharvest. *Each value* is the mean of 160 measurements (40 fruits per replication)

Table 3 Flower density, fruit set and trunk cross-sectional area (TCSA) average values as a function of treatment during the 3 years of the experiment

	Flower density ($Fl\ cm^{-1}$)	Fruit set (%)	TCSA (cm^2)
2008			
C	0.3a	60.3a	151.5a
RDI I	0.3a	58.7a	149.8a
RDI II	0.2a	66.7a	147.0a
2009			
C	0.5a	78.4a	180.7b
RDI I	0.6ab	79.7a	175.1ab
RDI II	0.7b	85.4a	162.7a
2010			
C	0.2a	87.0a	208.4b
RDI I	0.4b	91.3a	188.1a
RDI II	0.3ab	94.8a	186.5a

Each data point is the mean of 160 values per treatment (fruit set and flower density) and 64 values per treatment (TCSA). Different letters next to a value in each year indicate significant differences according to Tukey's multiple range test ($p < 0.05$)

compared to full irrigation conditions (Table 4), as previously reported in similar studies (Bradford and Hsiao 1982; Pérez-Pastor 2001; Girona et al. 2003, 2005; López et al. 2008; Abrisqueta et al. 2010). This reduction seems to be directly related to the amount of water applied (Fig. 8) and is desirable for high-density orchards in order to optimize tree light interception and improve economic revenues (Chalmers et al. 1981) due to lower operational costs.

In contrast to vegetative growth, fruit growth was not reduced by water deprivation during stage II and postharvest (Fig. 7b). In fact, similar crop loads and yields were observed for RDI treatments when compared to C trees. This trend was maintained for the 3 years of the experiment. As a consequence, greater IWP values were observed for the RDI treatments. Moreover, flower density and fruit set were only slightly affected by RDI, suggesting that withholding water during postharvest did not cause any carryover effect from year to year in a medium term. This is in contrast to previous results (Girona et al. 2003) and can be explained by the greater soil depth and rainfall distribution in our study.

Fruit distribution into marketable categories was unaffected by the irrigation treatment in any of the 3 years studied. Fruit destination caused a lower thinning in 2009 with respect to those of 2008 and 2010. In fact, peach was destined to the fresh market in 2008 and 2010, whereas it was sold to food industry in 2009 for obtaining canned fruits. Consequently, trees had a greater crop load and Ψ_s values in 2009 were more negative compared with those from the other years. This result is supported by previous reports on the effect of crop load on plant water status (e.g., López et al. 2010).

The year 2009 was different than the other two experimental years due to higher crop loads derived from the destination of the fruit, as already explained. Since the trees from all treatments were more loaded than the other experimental years, higher yields were obtained in 2009 for all treatments. In order to support these crop loads, trees developed greater canopies than in the other 2 years and thus increases in pruning weight were observed. The development of dense canopies and the high crop loads caused increased water demands in 2009, and hence, the peach trees experienced more water stress this year than in 2008 or 2010.

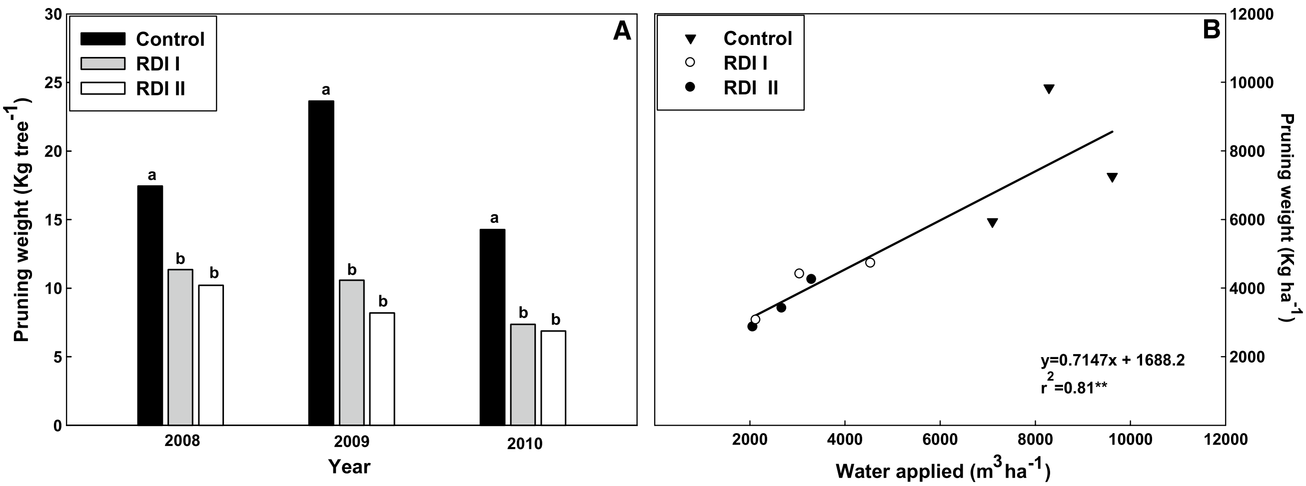

Fig. 8 **a** Pruning weight as a function of the irrigation treatment, control (*black bars*), RDI I (*gray bars*) and RDI II (*white bars*) in the 3 years of the experiment. *Each bar* corresponds to the mean of four values (average of four replications per treatment). *Different letters* on *top of bars* indicate significant differences according to Tukey's multiple range test ($p < 0.05$). **b** Relation between average pruning weight and water applied in C (*closed triangles*), RDI I (*open circles*) and RDI II (*closed circles*) plants for the 3 years of the experiment. *Solid line* represents the linear regression between pruning weight and water applied. *Asterisks* indicate a significant relationship between variables ($p < 0.01$)

Table 4 Crop load (number of fruit tree^{-1}), yield (t ha^{-1}), average fruit weight (g), irrigation water productivity (IWP, kg m^{-3}) and water applications/savings with respect to ET_c in each non-critical period and total in RDI treatments for the years of the experiment

	Crop load (fruits tree^{-1})	Yield (t ha^{-1})	Average fruit weight (g)	IWP (kg m^{-3})	Water savings (%)		
					SII	Postharvest	Total
2008							
C	170a	12.4a	174.9a	1.29a			
RDI I	137a	11.2a	196.0a	2.47ab	97	74	38
RDI II	160a	12.4a	185.9a	3.75b	99	92	55
2009							
C	489a	28.0a	137.3a	3.30a			
RDI I	523a	27.7a	127.0a	9.73b	98	80	59
RDI II	488a	26.3a	129.2a	10.63b	99	92	64
2010							
C	173a	12.6a	174.7a	1.77a			
RDI I	197a	14.1a	171.6a	6.61b	99	98	67
RDI II	244a	16.8a	165.9a	8.15b	99	99	68

Different letters next to a value in each year indicate significant differences according to Tukey's multiple range test ($p < 0.05$). SII indicates stage II of fruit development

Improvements in fruit taste and quality are expected for RDI treatments due to increased SSC (Crisosto et al. 1994; López et al. 2011; Alcobendas et al. 2013) that may reflect changes in the sugar composition of the fruit (Mirás-Avalos et al. 2013). Our results showed significant increase in SSC for RDI treatments (Table 5). Moreover, the ratio SSC/TA was greater for fruit from the RDI treatments. This may affect taste perception (Crisosto et al. 1997; Scandella et al. 1997) by the consumer, which might have implications in buying decisions.

Finally, when comparing the combination of deficit irrigation during stage II and postharvest with fully irrigated trees, higher water savings were achieved, up to 65 % in the case of RDI II for 2010 (Table 4). Hence, water savings depended on the Ψ_s threshold used and on climate conditions of the specific year. As reported by Girona et al. (2003), the level of water savings during postharvest was much greater than that of stage II, making postharvest a more appealing period than stage II for saving water. Several studies on other fruit tree crops support these findings

Table 5 Fruit firmness (N), pH, soluble solids content (SSC, °Brix), titratable acidity (TA, g 100 mL^{-1}) and SSC/TA ratio at harvest for all treatments

	Firmness (N)	pH (–)	SSC (°Brix)	TA (g 100 mL^{-1})	Maturity index (SSC/TA)
2008					
C	50.5a	4.13b	10.6a	0.59a	18.8a
RDI I	48.8a	3.98a	11.2a	0.52a	21.9b
RDI II	51.7a	3.92a	11.2a	0.54a	21.8b
2009					
C	49.3a	3.86a	10.6ab	0.61a	17.9a
RDI I	49.1a	3.93b	10.4a	0.57a	18.8a
RDI II	51.5a	3.82a	11.4b	0.61a	19.2a
2010					
C	52.2a	3.88a	11.5a	0.75b	15.6a
RDI I	56.5a	3.97a	12.1ab	0.64a	19.2b
RDI II	56.5a	3.88a	13.1b	0.72ab	18.2b

Values are the mean of 100 measurements. Different letters next to a value in each year indicate significant differences according to Tukey's multiple range test ($p < 0.05$)

(Romero et al. 2004; Girona et al. 2006; Pérez-Pastor et al. 2009).

The major effects of RDI in this study were related to reduction in vegetative growth and improvement in fruit quality, whereas crop yield remained unaffected. From a viewpoint of sustainability of water resources, RDI allowed reduced water consumption of around 55 % on average for the three studied years. However, these water savings were dependent on the values of the Ψ_s thresholds used, which must be adapted to the specific climate conditions of the site where they will be used (Ghrab et al. 2013) in order to reach the desired water stress.

Conclusions

Our results showed that using Ψ_s thresholds for scheduling irrigation in mid–late maturing peach trees under Mediterranean conditions is a viable option to save water without compromising yield. In this experiment, a Ψ_s threshold of −1.8 MPa at stage II of fruit development and −2.0 MPa at postharvest induced water savings up to 68 % over the growing season as compared to full irrigation based on micrometeorological data (ET_0).

Tree vegetative growth was restricted by RDI, and this trend was maintained over the whole experiment. This feature may be of interest for growers since lower costs for pruning operations (reduced work-time) are expected.

Fruit set, crop load and yield were unaffected by the RDI strategies considered. In addition, chemical attributes indicated a slight improvement in fruit quality under the RDI treatments. However, carryover effects from year to year need to be assessed for the long term. Hence, further experiments are required in order to evaluate the sustainability of the strategies considered in this study as well as to adapt the Ψ_s thresholds to other soil and climate conditions.

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Compliance with ethical standards

Conflict of interest The authors declare that no conflicts of interest exist.

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