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ORIGINAL PAPER

Benefits of low-frequency irrigation in citrus orchards

Iván García-Tejero · Víctor Hugo Durán-Zuazo · José Luis Muriel-Fernández · Gonzalo Martínez-García · Juan Antonio Jiménez-Bocanegra

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Abstract Citrus is a crop of major economic importance in Spain, cultivated during the dry season when irrigation is essential to guarantee yields of high quality. As water resources are progressively more insufficient, more effective water management in agriculture is crucial. Deficit irrigation in many agricultural crops has frequently proved to be an efficient tool for improving water-use efficiency. We hypothesise that, despite the effectiveness of deficit irrigation, the most suitable strategy in citrus orchards remains to be defined for Mediterranean environment. In this study, for the period from 2006 to 2008, a 12-year-old orange orchard, *Citrus sinensis* L. Osb. cv. Navelina, grafted onto Carrizo citrange, *C. sinensis* L. Osb.×*Poncirus trifoliata* L. Osb., were subjected under two deficit-irrigation strategies defined as follows: (1) low-frequency deficit irrigation applied according to the plant–water status, and (2) sustained-deficit irrigation with a water-stress ratio of 0.6, defined as the ratio of actual water-limited supply in this treatment related to the water supply of the control treatment. The control treatment was irrigated at 100% of ET_C for the entire irrigation season (ET_C: crop evapotranspiration). Midday stem–water potential (Ψ_{stem}) and stomatal conductance (g_S) were used to estimate the water status of the trees. The lowest Ψ_{stem} and g_S values were registered in the deficit-irrigation treatments with a seasonal pattern consistent with the irrigation dynamics applied in each case. Ψ_{stem} and g_S values significantly differed from those of the control trees. Although the integrated stress levels were similar in deficit-irrigation treatments, differences in yield and fruit quality were found, having a more positive response to low-frequency deficit irrigation with an increase of 25% in yield in comparison to the sustained-deficit irrigation treatment. Here, we thus demonstrate the significant differences in water productivity. Indeed, water productivity parameter not only depends on the amount of water, but also on the irrigation strategy applied, which promoted substantial water savings without significant impact on yield. The present study highlights that low-frequency deficit irrigation should be adopted as a most appropriate strategy for achieving sustainable water management and attains reasonable yields and improves quality in citrus orchards under Mediterranean semiarid climate.

Keywords Sustained deficit irrigation · Low-frequency deficit irrigation · Integrated stem–water potential · Integrated stomatal conductance · Yield · Fruit quality

1 Introduction

Water is key to agricultural security in Mediterranean arid and semi-arid areas, such as the Guadalquivir river basin (SW Spain). That is, water is the main limiting factor for the crop development, with an annual accumulated water deficit of nearly to 800–1,100 mm $year^{-1}$, and high variability of rainfall distribution, with several months (June to September) of low or zero rainfall, and average potential evapotranspiration of nearly to 7 mm day^{-1}. Therefore, this promotes that during the maximum evapotranspirative demand period, the crops require irrigation water inputs for responding to the crop water demand. In

I. García-Tejero · V. H. Durán-Zuazo (✉) ·
J. L. Muriel-Fernández · G. Martínez-García ·
J. A. Jiménez-Bocanegra
IFAPA Centro Las Torres-Tomejil,
Carretera Sevilla-Alcalá del Río km 12,2,
41200 Alcalá del Río, Sevilla, Spain
e-mail: victorh.duran@juntadeandalucia.es

this type of environment, the large inter-annual variability in rainfall is between the 250 and 475 mm. The most recent forecast for climatic change suggests significant changes in rainfall, leading to a 17% decline in the water resources available for agriculture worldwide (Iglesias et al. 2007). Consequently, climatic predictions for 2050 emphasise an increase in crop evapotranspiration of more than 20% in the Guadalquivir river basin, and these conditions will be more severe in the most western area, where the majority of arable land is concentrated (Rodríguez et al. 2007). In this context, the latest climate change predictions for Spain during this century suggest a significant increase in temperature (0.4°°C to 0.7°C per decade) with a reduced and altered annual rainfall distribution. These future scenarios, coupled with a growing demand for water resources, motivate to need of seeking strategies for optimising water-use efficiency and maintain the viability of agricultural ecosystems, focusing on maximising water savings and improving its productivity. An approach to increase irrigation efficiency is deficit irrigation, based on the application of a water restriction with a minimal impact on crop yield, without compromising the sustainability of agro-ecosystems (Paly and Zell 2009).

Basically, there are two methods to implement deficit irrigation for a crop: (1) by reducing the amount of irrigated water applied, and (2) by increasing the period between irrigation cycles. However, water deficit promotes a reduction in crop evapotranspiration and consequently, a reduction in photosynthetic rates and CO_2 fixation (Hsiao 1973), which can negatively affect the vegetative development and crop yield (González and Castel 2000). Deficit irrigation strategies should take into account the agronomic conditions of the crop, as well as nitrogen nutrition, edapho-climatic characteristics of the area, the periods of maximum evapotranspirative demand and the most critical growth periods, during which water should not be withheld (García-Tejero et al. 2010a).

In recent years, many studies in different environments have highlighted the advantages of using deficit irrigation to improve water-use efficiency and fruit quality in citrus trees (Sánchez et al. 1989; Ginestar and Castel 1996; González and Castel 1999, 2000; Muriel et al. 2006; García-Tejero et al. 2008, 2010a, b). Similar results have been reported for other fruit trees such as pear (*Pyrus communis* L.) (Kang et al. 2002; Naor et al. 2000), mango (*Mangifera indica* L.) (Spreer et al. 2007), almond (*Prunus dulcis* (Mill.) D.A. Webb; Goldhamer et al. 2006), nectarine (*Prunus persica* (L.) Batsch var. nectarina (Ait.) Maxim.; Naor et al. 1999), peach (*P. persica* (L.) Batch; Girona et al. 2002, 2003), apple (*Malus domestica* (L.) Borkh; Van Hoojdonk et al. 2004; Naor et al. 1995; 1997; Naor and Cohen 2003), and grape (*Vitis vinifera* L.; Girona et al. 2006). Today, research advancements have led to innovative techniques for improving water-use efficiency in agricultural systems. Therefore, efficiency in irrigated agriculture has become key in sustainable water management, especially in Mediterranean areas, where the water is the limiting resource for crop production. Thus, adopting water-saving strategies for efficient water use in agriculture is becoming fundamental.

The aim of the present work, over a 3-year monitoring period, was to assess the agronomic benefits of two deficit-irrigation strategies with similar water consumptions that differed in their scheduling: low-frequency deficit irrigation and sustained deficit irrigation for citrus orchards under semi arid Mediterranean climate of SW Spain.

2 Materials and methods

2.1 Experimental site

The trial was conducted in a commercial orchard of 12-year-old sweet orange (*Citrus sinensis* (L.) Osbeck cv. Navelino) grafted onto Carrizo citrange (*C. sinensis* (L.) Osbeck× *Poncirus trifoliata* Raf.), located in the Guadalquivir river basin, SW Spain (37° 29′ 18.85″ N; 5° 50′ 42.67″ W) over a 3-year period. Trees, which averaged 2.5 m in height with a canopy diameter of 2.2 m, were spaced 6 m×4 m with a NS orientation on ridges of 0.4 m high and 2.5 m wide, with a standard distance of 3.5 m between ridges. Drip irrigation was supplied by two pipe lines with pressure-compensated emitters having a flow rate of 2.2 L h^{-1}. Root depth was about of 0.5 m, although the 90% of active roots were located within 0.3 m depth. Shaded soil surface area and wet drip zone were 20% and 14%, respectively. Total study area was 3.2 ha, with a conventional management since planting, according to legal policies published for agricultural integrated production for citrus in Andalusia, Spain (BOJA 2000).

The soil of the experimental site was typical fluvisol (Soil Survey Staff 2006), with 0.9 m depth and with a significant clay accumulation at 1 m depth. The soil texture was sandy loam, with 700 g kg^{-1} of sand, 190 g kg^{-1} of silt, and 110 g kg^{-1} of clay. The organic-matter content was below 1%, and a soil water-holding capacity of 110 mm m^{-1}.

The local climate is typically Mediterranean-dry with an average potential evapotranspiration (ET_0) of 1,400 mm yr^{-1} and an annual rainfall of 475 mm, with a seasonal pattern, distributed mainly from November to April and with a high annual variability. The winter temperatures are mild, rarely below 0°C, with very hot summers, temperatures in many cases exceeding of 40°C. This promotes a high water demand by the plants, with a crop evapotranspiration (ET_C) of nearly 5 mm day^{-1}.

2.2 Irrigation treatments and experimental design

Two deficit-irrigation treatments were tested: sustained deficit irrigation with an application of 60% of ET_C and low-frequency deficit irrigation applied according to the plant's water status. The low-frequency deficit irrigation was similar to the conventional irrigation regimen in the study area, when the water supply was made by flooding, with a periodicity of 7–10 days, allowing a partial depletion of soil water content. In our case, the irrigation restriction cycles were established according to the stem–water potential at midday (Ψ_{stem}). When this parameter approached −2.0 MPa, the trees under this treatment were irrigated, covering the total ET_C (approximately during 7–10 days). When Ψ_{stem} values in this treatment were similar to Ψ_{stem} values for control treatment, irrigation was withheld until the Ψ_{stem} values were approached the threshold value of −2.0 MPa. Deficit irrigation was applied between May (in the early fast-growth fruit period) and November, when maximum evapotranspirative demand period was ending (fruit-maturity period had been finished). The control treatment (C) was irrigated at 100% of ET_C during the irrigation season.

Analogical flow meters were used to measure the amount of irrigation water applied to each treatment. The number of drip emitters per tree ranged between eight for control and low-frequency deficit irrigation and four sustained deficit irrigation, respectively.

The volume of water applied was calculated, using the Doorenbos and Pruitt (1977) equation:

$$ET_c = \sum_{1}^{7} \left[(ET_0 \cdot K_c \cdot K_r) - rain \right] \tag{1}$$

where ET_C is the crop evapotranspiration under standard conditions, K_C is a crop coefficient, and K_r is a reduction coefficient, calculated as twice the ratio of the shaded surface at noon (Castel 1991). The K_C values were based on guidelines provided by Allen et al. (1998). In our case, we used a K_r of 0.6 and a K_C that was a function of the seasonal period (January–February 0.45; March to May 0.5; June to October 0.55; November to December 0.5).

During the maximum evapotranspirative period, control and sustained deficit irrigation trees were irrigated with the same periodicity (three times per week, on average); and low-frequency deficit irrigation with this same frequency during the irrigation recovery periods.

The three irrigation treatments were displayed in a randomised-block design with three replications. Each plot had eight trees per row. The four central trees of the rows were used for fruit yield and physiological measurements while the other four trees served as border trees. The experimental orchard was managed according to commercial practices in the area, with the same fertilisation (150, 70 and 110 kg ha^{-1} N, P_2O_5, and K_2O, respectively), and routine management techniques for diseases and insect control were used.

2.3 Plant measurements

During the maximum evapotranspirative demand period of the studied years, the Ψ_{stem} was measured with a pressure chamber (Scholander et al. 1964), following Turner (1988) methodology, in two leaves per tree. The measurements were made between 10:00 and 12:00 h solar time every 7–10 days, in shaded mature leaves close to the north quadrant and near the trunk. The Ψ_{stem} is the most accepted technique for measuring the water-stress signal for plants.

With a similar periodicity and sampling period, during the 2007 and 2008 seasons, stomatal conductance (g_S) was monitored in two sunny leaves per tree, using a diffusion porometer AP-4 (Delta-T Devices, Cambridge, UK). This measurement is the inverse of stomatal resistance to the moving of CO_2 and $H_2O_{(v)}$ throughout the stomatal pores, and it is closely related to the water-stress level tolerated by the plant. Verasan and Phillips (1978) proposed the use of cumulative plant transpiration as a good integrator of the effects of water stress. Plant transpiration is closely related to g_S, although it is affected by several climatic variables as well as by plant–water stress (Anapalli et al. 2008).

The water stress accumulated by the crop was estimated by calculating the integrated stem–water potential (Ψ_{Int}), according to the modified equation by Myers (1988), which integrates the water-potential values with the time during which the trees become stressed (García-Tejero et al. 2010a):

$$\psi_{int} = \sum_{i=1}^{i=t} \left| \psi_{i+1} \times (n_{i+1} - n_i) + \frac{1}{2} \left(\psi_i - \psi_{i+1} \right) \times (n_{i+1} - n_i) \right| \tag{2}$$

where: Ψi, and Ψ_{i+1} are the measured stem–water potential values on two different sampling days (i and i+1) and n_i and n_{i+1} are the corresponding days of serial sampling.

This equation shows the value of the defined integral by the function of Ψ_{stem} curve at a given time interval, and it is related to the accumulated water stress during a time interval.

Integrated stomatal conductance was calculated also by Eq. 3 for only 2 years (2007–2008). This data shows the accumulated stomatal conductance by the crop during the irrigation period (García-Tejero et al. 2010b):

$$g_{Int} = \sum_{i=1}^{i=t} \left| g_{i+1} \times (n_{i+1} - n_i) + \frac{1}{2} (g_i - g_{i+1}) \times (n_{i+1} - n_i) \right| \tag{3}$$

where: $g_{i,}$ and $g_{i,+1}$ are the stomatal-conductance values on two different sampling days (i and i+1) and, n_{i+1} and $n_{i,}$ the days corresponding to two serial days of sampling.

Fruit diameter was measured in 24 fruits per tested tree with the same periodicity of Ψ_{Stem} or g_S measurements, using a digital calliper to assess the response of fruit size evolution to irrigation treatments during the fruit-growth stage.

As a means of determining the effects of deficit irrigation, the fruit yield was recorded for each tree. Also, 100 fruits per tree were sampled to determine fruit weight. Fruit number per tree was determined as the ratio between tree yield and the average fruit weight, while water productivity was calculated as the ratio between final yield (kilogramme per tree) for each treatment and the amount of water applied (effective rainfall+irrigation water).

Finally, the fruit-quality characteristics were analysed at harvest with ten fruits per tree, including morphological properties: rind weight (%*w/w*), equatorial diameter (millimetres), and polar diameter (millimetres); as well as the commercial parameters such as total soluble solids (TSS; ºBrix), titrable acidity (TA; grammes per liter), maturity index (TSS TA^{-1}) and juice weight (% *w/w*).

2.4 Statistical analysis

An exploratory and descriptive analysis was made of yield and its components, followed by analysis of variance (ANOVA) with a mean separation analysis. Similar analysis of physiological parameters ($\Psi_{sten,}$ $\Psi_{Int,}$ g_s and g_{Int}, respectively), was performed to evaluate the accumulated effects of crop-water stress.

An overall analysis of yield and its components was made by the 3 years of collecting data. The annual datasets were homogenised, according to the methodology proposed by Sterk and Stein (1997).

3 Results and discussion

3.1 Weather conditions and water relations

The pattern of ET_C and rainfall were very similar during the 3 years, with an irregular distribution and a scarcity of rainfall between June and October (Table 1). Daily ET_C and rainfall during this irrigation period were 1.85 and 0.62 mm, respectively, with a water deficit close to 190 mm (Table 1). The previous temporal distribution of rainfall at the end of fruit-growth period required irrigation, taking into account that, during this period, rainfall and accumulated ET_C were close to 0 and 180 mm, respectively (Table 1, Fig. 1). Water supplied during the three seasons was similar, with a coefficient of variation of less than 5% for all treatments. Regarding sustained deficit irrigation treatments, this received daily irrigation water amounts of 0.95, 0.92 and 1.09 mm during the irrigation periods in 2006, 2007, and 2008, respectively. On the other hand, low-frequency deficit irrigation received 1.08, 1.09 and 1.25 mm per day during the irrigation periods for 2006, 2007 and 2008, respectively. Finally, the control treatment received daily irrigation-water amounts of 1.67, 1.62 and 2.11 mm for the 3-year monitoring period. These differences between treatments promoted water savings of nearly 125 and 102 mm for sustained deficit irrigation (water-stress ratio of 0.55) and low-frequency deficit irrigation (water-stress ratio of 0.63), respectively (Table 1). While the difference between these treatments in daily irrigation amounts were not remarkable (3.68 L $tree^{-1}$ day^{-1} over low-frequency deficit irrigation treatment), the irrigation dynamics were very different. Therefore, trees under the low-frequency deficit irrigation treatment were subjected to irrigation-restriction

Table 1 General climatic conditions and irrigation water applied, water–stress ratio and water savings for each treatment during the study seasons. *C* control, *SDI* sustained deficit irrigation, *LFDI* low-frequency deficit irrigation, *IP* irrigation period, *DOY* day of the year, ET_C estimated crop evapotranspiration, *WSR* water–stress ratio, defined as the actual ratio of water supplied to each treatment referred to control treatment, *WS* water saving in relation to control treatment

Weather conditions		2006	2007	2008
IP (days)		170	163	134
DOY		118–288	131–294	152–286
ET_C (mm)		330.9	283.3	251.1
Rainfall (mm)		119.6	109.8	66.8
Treatments				
LFDI	Irrigation (mm)	183.7	174.6	168.4
	WSR	0.65	0.66	0.59
	WS	100.1	89.2	114.9
SDI	Irrigation (mm)	161.8	149.2	146.5
	WSR	0.57	0.57	0.52
	WS	122	114.6	136.8
C (100% ET_C)	Irrigation (mm)	283.8	263.8	283.3
	WSR[4]	1	1	1
	WS[5]	0	0	0

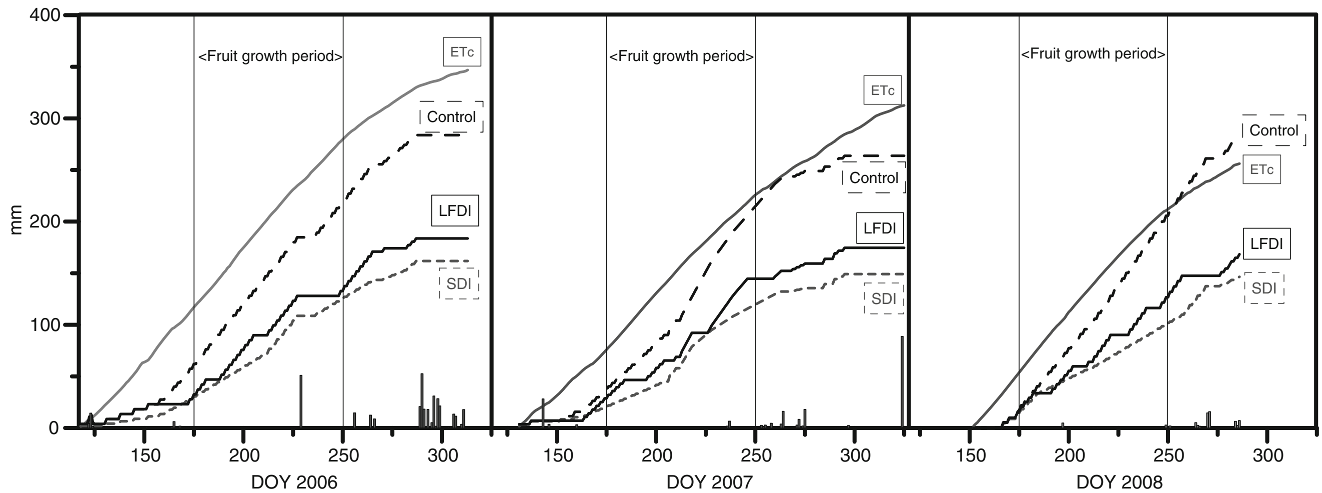

Fig. 1 Irrigation and accumulated crop evapotranspiration (ET_C) during the 3-year monitoring period. *Vertical bars* correspond to the rainfall registered during the irrigation period. Control, SDI and LFDI are the different irrigation treatments (SDI, sustained deficit irrigation; LFDI, low-frequency deficit irrigation). Axis *X* units correspond to the days of each study year

cycles, while trees under sustained deficit irrigation treatment were irrigated at the same time as the control trees but with a different amount of irrigation water, causing the curves of cumulative irrigations in this treatment to have a slope lower than for the control treatment (Fig. 1). On other hand, in low-frequency deficit irrigation treatment, this trend showed a time period without growth, which coincided with the restriction cycles.

Finally, the fruit-growth period was the most critical stage and more noticeable given the climatic conditions registered, due to the high crop evapotranspiration and the scarcity of rainfall. Thus, the application of a water deficit during this stage and under these Mediterranean weather conditions must been taken into account in order to assess the possible effects on citrus yield (García-Tejero et al. 2010b).

3.2 Water deficit and crop response

Seasonal pattern of Ψ_{Stem} was consistent with the different water inputs and applied irrigation strategy (Fig. 2). Average values in the control treatment calculated during the 3 years ranged between −0.7 and −1.3 MPa, depending on the time of measurement. The lowest Ψ_{Stem} values in this treatment were registered during the fruit-growth period, when the weather conditions were especially severe. These findings were close to those reported by Ortuño et al. (2006), where the threshold value of −1.3 MPa is indicated for well-watered citrus trees. The time course Ψ_{Stem} values in deficit irrigation treatments were consistent with the irrigation strategy. Therefore, the low-frequency deficit irrigation fluctuated markedly with the irrigation dynamics. During the restriction cycles, Ψ_{Stem} gradually decreased to a tolerable threshold value of $\Psi_{Stem,}$ approximately between −2.0 and −2.5 MPa. At this stage, this treatment was irrigated with the same amount of water and frequency as the control treatment, until it partially recovered the corresponding Ψ_{Stem} of the control trees. At that time, the irrigation was halted, and a new restriction–recovery cycle started. Measurements of Ψ_{Stem} in the sustained deficit irrigation treatment showed a progressive decline, reflecting a gradual crop water–stress accumulation over time. Only at two points in time during 2006 and 2007, additional irrigations (applying the 100% of ET_C) were needed to recover plant–water status, due to the stress level endured by the crop. De Swaef et al. (2009) reported that Ψ_{Stem} is highly related with the plant water status, bearing strong relationships with other parameters such as sap-flow rate or radial-stem growth. García-Tejero et al. (2010a, b) pointed out that this variable was strongly related to the irrigation level applied in citrus tress cv. Navelina and cv. Salustiana.

The Ψ_{Int} data were consistent with the pattern noted in the time course of Ψ_{Stem} (Fig. 3). Also, it was remarkable that low-frequency deficit irrigation and sustained deficit irrigation treatments did not show significant differences between them although their time course differed, reaching similar levels of accumulated water stress. For the control treatment, Ψ_{Int} values were significantly lower ($p<0.05$) than those observed in the deficit-irrigation treatments for the entire study period, with Ψ_{Int} values being 50% lower than those found in the deficit treatments.

The g_s and g_{Int} evolution throughout the monitoring period showed a similar pattern to that of Ψ_{Stem} and Ψ_{int}, respectively, with significant decreases ($p<0.05$) in the deficit irrigation treatments compared with the control treatment (Figs. 4 and 5). In sustained deficit irrigation, the stomatal conductance was significantly lower ($p<0.05$) than in the control treatment, with a progressive decline

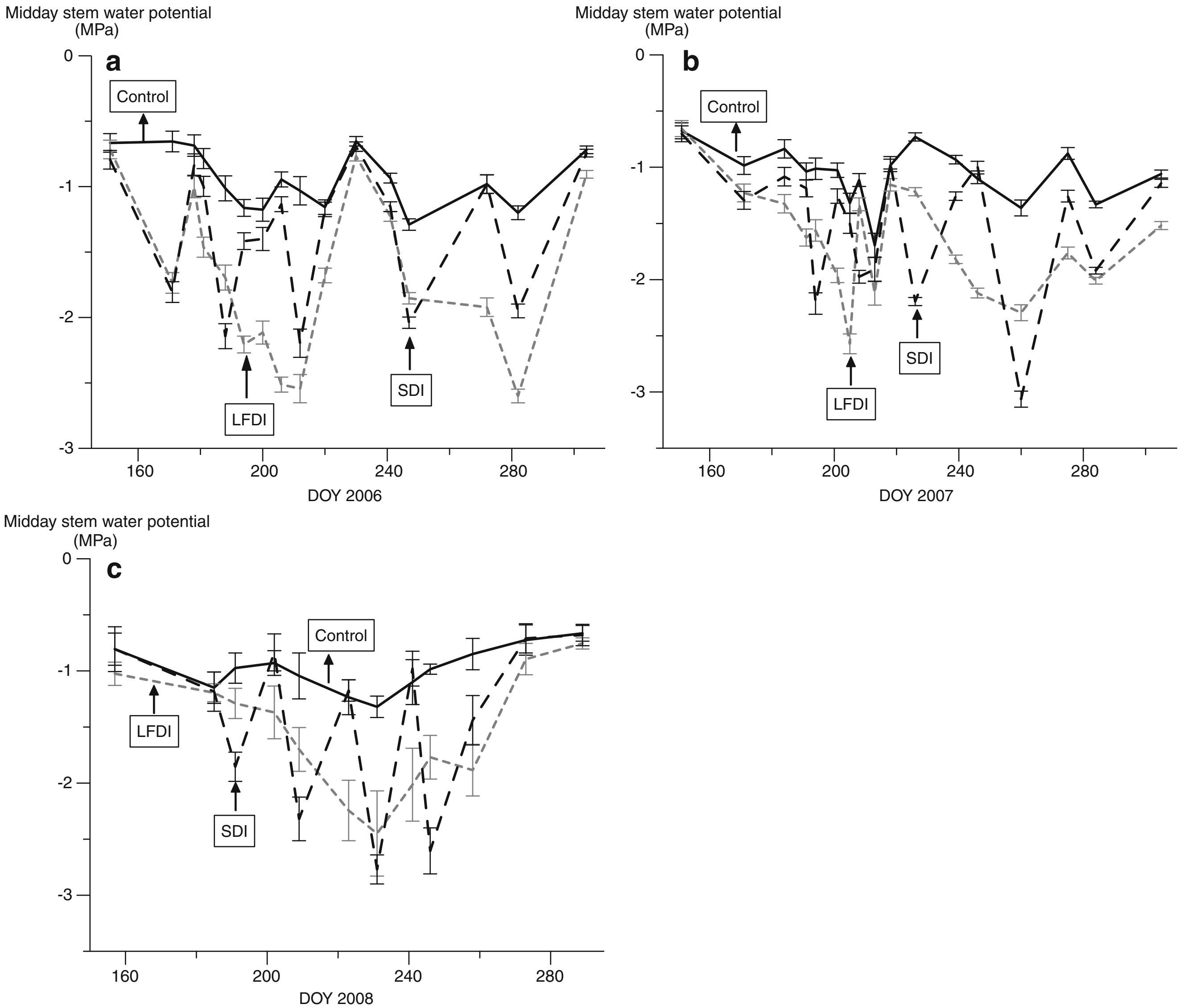

Fig. 2 Time course of midday stem–water potential in each treatment for the 3-year monitoring period. *DOY* day of the year, *SDI* sustained deficit irrigation, *LFDI*, low-frequency deficit irrigation

during the sampling period of stomatal-conductance values. In addition, the pattern of this variable for low-frequency deficit irrigation was closely similar to Ψ_{Stem} in this treatment (Figs. 4 and 2). By taking into account the Ψ_{Int} values, the g_{Int} showed significant differences between treatments with a similar statistical classification between treatments. Consequently, the water stress tolerated by sustained deficit irrigation and low-frequency deficit irrigation strategies was very similar (Fig. 5) with a difference only in the temporal pattern (Fig. 4).

3.3 Water deficit and fruit growth

During the fruit-growth stage, the temporal equatorial diameter variation was tracked to determine the water–stress effects on this parameter. First of all, the differences between treatments were detected throughout the fruit-growth phase, although the highest difference among their growth trends occurred between days 180 and 200, coinciding with the period having the highest growth rate. Previously, some fruit differences had been detected, and these were monitored during the remaining fruit-growth period (Fig. 6a, c). The water stress caused by the different deficit-irrigation treatments promoted remarkable effects in these trends (Fig. 6a, b, c). The increase of slope in sustained deficit irrigation treatment was significantly lower than in the control treatment ($p<0.05$). Indeed, in some sampling times, stop-situations of fruit growth were detected, presumably due to high evapotranspiration conditions during these periods (Fig. 6b, c). On the other hand, the fruit growth time course

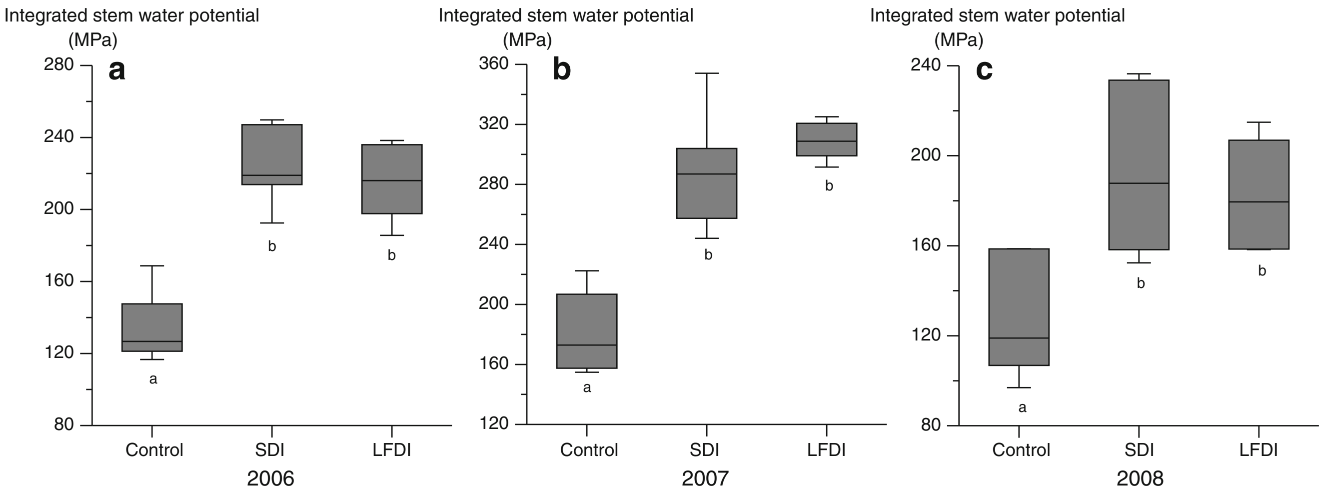

Fig. 3 *Box* and *whisker plot* for integrated stem–water potential during the study years. *Vertical lines* indicate the standard deviation. Different letters indicate significant differences at $p<0.05$ by Tukey's test. *SDI* sustained deficit irrigation, *LFDI* low-frequency deficit irrigation

in the low-frequency deficit irrigation treatment showed remarkable differences with sustained deficit irrigation and control treatments. These trends registered sampling times without fruit growth and, indeed, with negative fruit growth. Moreover, this treatment showed even higher growth rates than those recorded for the control treatment, when it was subjected to the recovery risks. This effect allowed a less significant effect of water stress in this treatment compared with the recorded data for sustained deficit irrigation treatment. In this context, García-Tejero et al. (2010b) reported that this phase is the most critical for applying a water stress, since it can involve a crucial impact on yield, mainly due to a decrease in fruit size. Similar results were reported by other authors (Ginestar and Castel 1996; González and Castel 1999; Hutton et al. 2007).

3.4 Deficit irrigation impact on yield and fruit quality

In 2006, significant differences for the sustained deficit irrigation treatment were found in many productivity and quality parameters, which impacted clearly on fruit yield (Table 2). Sustained deficit irrigation treatment showed a yield reduction of 27% compared with control, with a significant impact detected in fruit weight, with reductions of 16% and in fruit number per tree (12%). Water stress also affected fruit size, with significant changes in polar and equatorial diameters (Table 2). The most noteworthy result refers to the absence of significant differences in terms of productivity (i.e., yield, fruit weight, equatorial diameter, polar diameter and fruit number) between control and low-frequency deficit irrigation treatments, with important

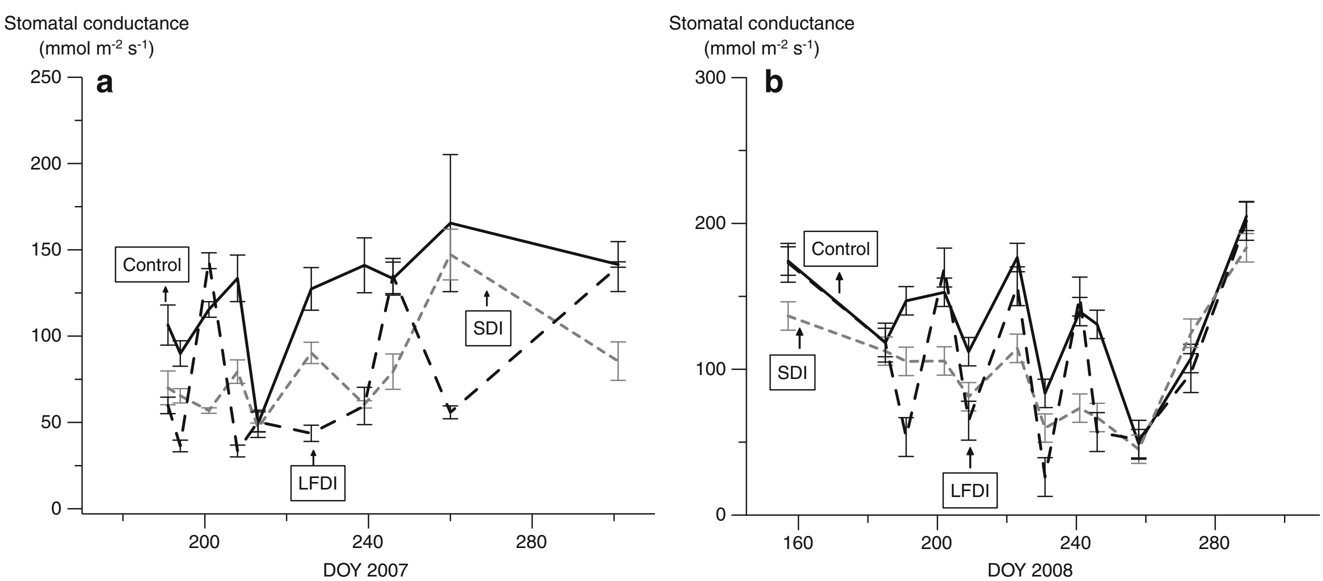

Fig. 4 Stomatal conductance evolution for each treatment during 2007 and 2008. *DOY* day of the year, *SDI* sustained deficit irrigation, *LFDI* low-frequency deficit irrigation

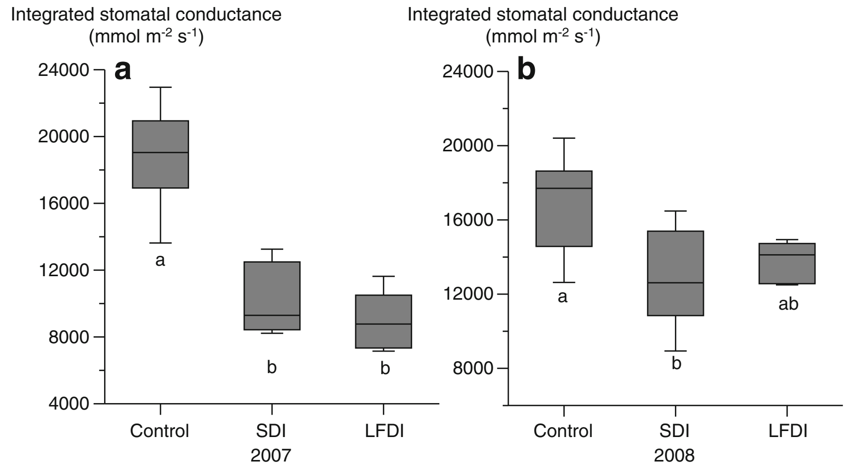

Fig. 5 *Box* and *whisker* plot for integrated stomatal conductance during the studied years. *Vertical lines* indicate the standard deviation. *Different letters* indicate significant differences at $p<0.05$ by Tukey's test. *SDI* sustained deficit irrigation, *LFDI* low-frequency deficit irrigation

implications for water savings. With regard to fruit-quality parameters, total soluble solids, titrable acidity, and maturity index were the most strongly affected by deficit irrigation. The data for sustained deficit irrigation were especially relevant, registering the highest values in total soluble solids and titrable acidity, which significantly differed from control values ($p<0.05$). In relation to maturity index, the control treatment registered the best results, being these significantly different from sustained deficit irrigation and low-frequency deficit irrigation data. Consequently, low-frequency deficit irrigation achieved substantial improvements in some of the organoleptic properties while maintaining acceptable yield values, with juice content similar to control treatment and significantly higher than for sustained deficit irrigation.

In 2007, yield showed characteristics similar to those of the 2006 season (Table 2). Significant differences ($p<0.05$) between sustained deficit irrigation and control treatments were found, with yield reductions of close to 30%. As in the previous season, the differences between low-frequency deficit irrigation and control treatment were not significant (with only a reduction in yield close to 7%). Similar to the 2006 season, other morphological parameters, such as fruit weight, polar and equatorial diameter, showed clear differences between control and sustained deficit irrigation treatment, whereas, in low-frequency deficit irrigation, these parameters did not significantly differ with respect to control. Additionally, juice and rind weight differed between control and deficit irrigation treatments with about 6% of juice-weight reduction and 6% increase in rind weight for the deficit-irrigation treatments, indicating a direct relationship between water stress and these parameters.

Finally, in 2008, the effects of water stress observed during 2006 and 2007 were again patent in this season (Table 2). There was a clear reduction in yield for the sustained deficit irrigation treatment, with a reduction of close to 25%. This was related mainly to a shrinkage in fruit diameters (equatorial and polar diameters), which significantly reduced fruit weight and fruit number per tree. Regarding low-frequency deficit irrigation, no significant effects of water stress was detected in the main productive parameters (yield, fruit weight and fruit number) in comparison to control. On other hand, there were remarkable effects on sustained deficit irrigation and low-frequency deficit irrigation related to the water stress such as an increasing in rind weight (up to 5% with respect to control treatment), which was accompanied by a significant decrease in juice weight (below to 5% with respect to control trees). Fruit organoleptic properties underwent effects similar to those detected in previous years, with a significant increase in total soluble solids and titrable acidity for sustained deficit irrigation and low-frequency deficit irrigation treatments and a decrease in maturity index. Moreover, this decline cannot be considered significant for low-frequency deficit irrigation in comparison to the control treatment.

The pooling of the data showed that the main water stress effects were related to yield, morphological and fruit-quality parameters. Hence, the rise in total soluble solids and titrable acidity values registered in the sustained deficit irrigation, and low-frequency deficit irrigation treatments were especially notable. Many studies have been pointed out that water stress in citrus crops affects these properties (Hockema and Etexeberria 2001; Bielorai 1982; García-Tejero et al. 2010a, b). Verreynne et al. (2001) reported that a conventional deficit irrigation strategy with water savings of 60–66% in relation to a control treatment, increased total soluble solids and titrable acidity in "Marisol" Clementines without affecting the juice content or reducing the fruit size. On the other hand, in terms of yield, the water-stress effects were closely related to the irrigation strategy, rather than amount of irrigated water. Many authors have pointed out that the response of citrus trees to water stress depends mainly on the crop phenology and physiological status, irrigation strategy and the degree of stress endured by the crop (Doorenbos and Kassam 1979; Ginestar and Castel

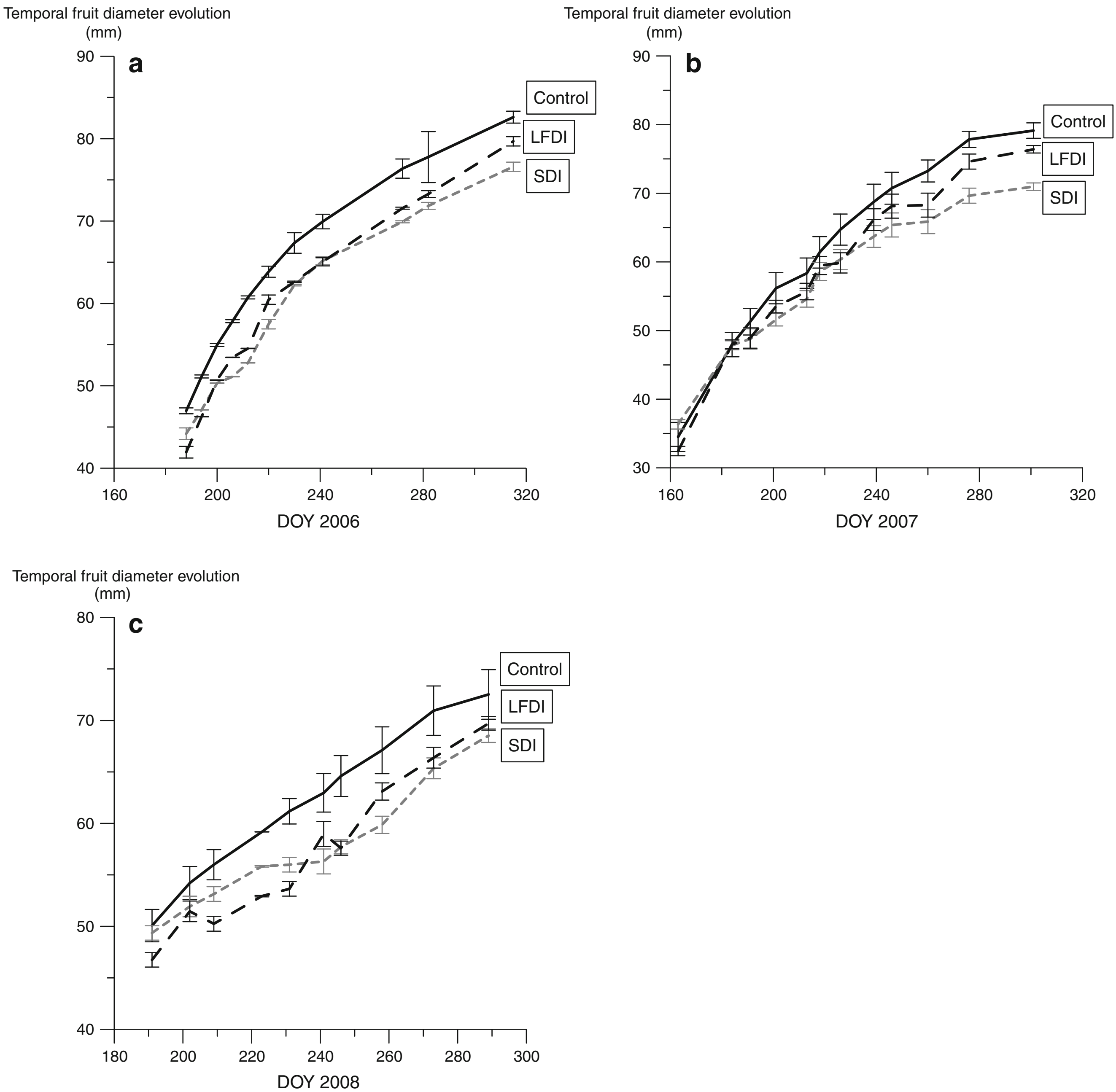

Fig. 6 Temporal fruit-diameter change during the fruit growth stage for each monitoring season. *Vertical lines* indicate the standard deviation for each treatment. *DOY* day of the year, *SDI* sustained deficit irrigation, *LFDI* low-frequency deficit irrigation

1996; García-Tejero et al. 2008, 2010b), and thus, a yield reduction can be promoted by the fall of flowers or young fruits (González and Castel 1999, 2000; Ginestar and Castel 1996) if water is restricted during the flowering period; or the fruit growth declines if the water stress is applied during the fruit-growth period (García-Tejero et al. 2010b). In our case, water deficit was applied from the end of flowering period to the middle of the maturity period. This explains the differences in fruit number per tree, fruit weight and organoleptic properties during the studied period. Sepaskhah and Kashefipour (1994) experimentally studied the response of sweet lime (*Citrus limetta*, Swing) to deficit irrigation based on different fractions of pan evapotranspiration (from 0.4 to 1.0). They reported that the maximum yield corresponded to the treatment with a water deficit of 25% with respect to control treatment, although, the effects of deficit irrigation were especially important in fruit weight, this being statistically different in control treatment, where the highest values were registered for this parameter. Moreover, yield as well as fruit weights were closely related

Table 2 Yield components and fruit-quality parameters for the study period

Season	2006			2007			2008		
	Control	SDI	LFDI	Control	SDI	LFDI	Control	SDI	LFDI
Yield (kg tree^{-1})	121.7a	88.4b	110.8a	116.3a	81.4b	108.3a	148.1a	108.9b	127.3ab
Fruit weight (g)	248.9a	208.8b	234.8ab	251.3a	142.2b	213.9a	242.6a	217.9b	220.8ab
Fruits per tree	490a	434b	476a	464a	583a	557a	617a	512b	580a
Juice weight (%)	49.1a	46.2b	50.5a	49.4a	43.8b	44.3b	49.9a	43.5b	44.6b
TSS (ºBrix)	11.5b	13.6a	12.2ab	11.4c	15.1a	13.7b	12.2b	12.5ab	13.5a
TA (g L^{-1})	1.01b	1.29a	1.21b	1.2b	1.8a	1.5ab	1.2b	1.5a	1.4a
MI	11.4a	10.5b	10.1b	9.5a	8.4b	9.1a	10.2a	8.3b	9.6ab
ED (mm)	83.7a	78.1b	81.5a	79.6a	71.4b	75.7ab	78.8a	73.4b	72.4b
PD (mm)	88.2a	79.3b	88.9a	79.9a	71.5b	76.6ab	88.5a	80.7b	79.5b
Rind weight (%)	49.7b	52.2a	49.1b	50.4b	56.5a	55.5a	49.9b	56.05a	54.5a

SDI sustained deficit irrigation, *LFDI* low-frequency deficit irrigation, *TSS* total soluble solids, *TA* titrable acidity, *MI* maturity index, *ED* equatorial diameter, *PD* polar diameter

to values of leaf-water potential recorded in the different treatments studied. In this same work, regarding the fruit-quality parameters, the most stressed treatments showed higher values in total soluble solids, acidity, and vitamin C. Thus, these same treatments showed higher values in rind weight and a lower maturity index.

Similar results were reported by Treeby et al. (2007) in navel orange, where deficit-irrigation treatments reduced fruit size and raised total soluble solids and titrable acidity values. In addition, Romero et al. (2006) found that severe deficit irrigation raises titrable acidity more than total soluble solids, affecting the final maturity index. This effect was observed in our results and may be related to the water-stress duration. In this context, Pérez-Pérez et al. (2009), studying 'lane late' sweet orange found that when water stress was applied during the phase III of fruit growth, there was an increase of total soluble solids and titrable acidity values, although maturity index was not affected. In this study, other parameters were affected by water stress such as fruit diameter, peel thickness, colour index, pulp and peel content (percent), and juice content, all of these agreeing with the results of the present experiment.

In relation to these results, the total soluble solids content is one of the parameters most affected by the crop water stress. The main cause is not clear, although some authors have explained that this fact can be promoted by a passive dehydration of juice sacs, accompanied by lower juice content (Pérez-Pérez et al. 2009). In our case, this could be the main factor, as the juice content was affected by the water stress. In this sense, Barry et al. (2004) suggested that the higher total soluble solids could be caused by osmotic adjustments in the juice cells.

3.5 Deficit irrigation and water productivity

Irrigation-water productivity, defined as the amount of harvested product per unit of water applied (rain and irrigation), was analysed. The results showed that sustained deficit irrigation and low-frequency deficit irrigation promoted increments in water productivity of close to 15% and 27%, respectively (Fig. 7).

However, the dynamic for each treatment differed for each year studied. Therefore, the differences in water productivity

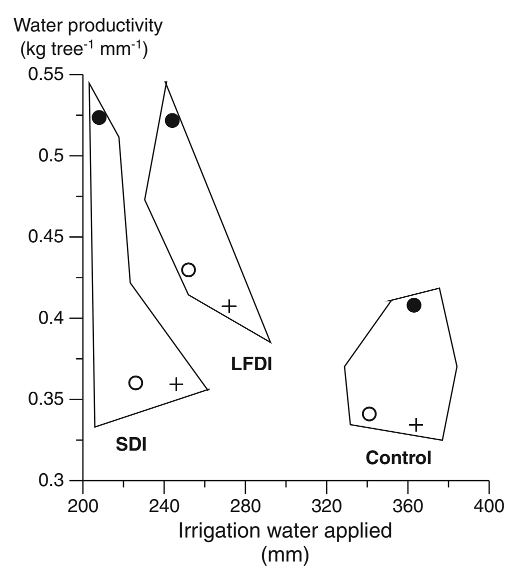

Fig. 7 Water productivity for each treatment during 3-year monitoring period. *SDI* sustained deficit irrigation treatment, *LFDI* low-frequency deficit irrigation treatment, *control* control treatment. *Cross*, *empty circles*, and *full circles* represent 2006, 2007, and 2008 periods, respectively

between sustained deficit irrigation and low-frequency deficit irrigation during 2006 and 2007 were notable, whereas, in 2008, these values were more uniform than for the remaining years. Despite that a reduction in irrigation water applied should be related to high water productivity, this relationship was not found in our experiment. The main reason for this may be related to the irrigation treatment, which in our case was more important than the total water consumed. Consequently, the crop water response to different deficit-irrigation strategies should be related not so much to water stress endured by the crop (Ψ_{Int} and g_{Int}) but rather the timing of that stress (Figs. 2, 3, 4, and 5).

It is crucial to emphasise these results in order to understand the water savings as well as the agronomic benefits of deficit-irrigation strategies. The appropriate water management by agriculture includes any strategy that promotes agro-ecosystem sustainability by achieving adequate yield with a significant water savings. Our results reveal that the impact of water stress in yield was governed by the irrigation strategy itself, rather than the amount of irrigation water applied. Many authors have concluded that deficit irrigation enhances the water productivity (Ali et al. 2007; Jalota et al. 2006) and can promote acceptable commercial yield. This improvement is vital in arid and semi-arid areas of the world, where the water availability is the most productive limiting factor. The best strategy of deficit irrigation is determinant for avoiding possible pernicious effects of water stress. In our case, low-frequency deficit irrigation proved to be the best deficit-irrigation strategy, improving water use in citrus and thereby maintaining almost similar yields as control trees. Therefore, although under this irrigation strategy, the yield reduction was close to 10% it was not statistically significant, whereas the water saving was nearly to 40%. On the other hand, this strategy implements the traditional irrigation system in this area, which consists of applying flooding from an irrigation ditch. The only adjustment required is that the grading system of the surface must have a slope that allows water breakthrough. In this approach, applied irrigation water was carried out with a periodicity of 7–10 days, allowing the soil to dry and applying irrigation when the soil water retained had been taken up by the crop. This conventional system has the advantage of being economical, but its efficiency is very low (25–35%) and consequently, the water productivity is wasteful. However, the implementation is high when water is extracted from wells or rivers. In our case, the irrigation–restriction cycles were established taking as a reference the crop-water status, with drip irrigation, which increases the water-use efficiency. Our results, suggest that this deficit-irrigation strategy, would foster sustainable agricultural development in areas with special conditions, such as the south-western of Spain, where the available water resources are very limited and the water demand is growing.

4 Conclusion

The increasing demand of irrigation water in the Mediterranean semiarid environment, together with the growing aridity from climate change, makes it necessary to apply appropriate measures aimed at a better management of irrigation systems as well as to evaluate specific operational and management decisions. According to the results of the present study, the deficit-irrigation strategies are a good choice for achieving more efficiency in irrigation-water use, increasing the water productivity by up to 30% with respect to well-watered treatments, with water savings of close to 1,000–1,250 m^3 ha^{-1}, which will be important in shortage periods due to climate change scenarios. Within these strategies, low-frequency deficit irrigation with a water-stress ratio of nearly 0.65 reflected improved fruit-quality parameters in comparison to the control treatment (100% ET_C) and no significant differences in yield. On the other hand, the low-frequency deficit irrigation strategy offers significant improvements in other organoleptic properties such as total soluble solids and titrable acidity. In addition, the results for sustained deficit irrigation treatment indicates that this irrigation strategy offers important water savings while improving some organoleptic properties such as total soluble solids and titrable acidity although, the productive parameters (yield, fruit weight, fruit number, equatorial diameter and polar diameter) may be significantly affected, failing to ensure optimal yield values and its profitability. This fact may be significant although the sacrifice in yield may be offset by the savings in water.

Thus, the low-frequency irrigation strategy is a promising alternative for increasing and maintaining the agronomic benefits for citrus orchards in Mediterranean semi-arid areas by promoting sustainable water savings especially in years with water availability below that required by the crop.

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