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Original Article

Long-term impact of sustained-deficit irrigation on yield and fruit quality in sweet orange *cv.* Salustiana (SW Spain)

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Abstract

Long-term impact of different sustained-deficit irrigation (SDI) treatments on a 13-year-old orange orchard (*Citrus sinensis L. Osbeck, cv. Salustiana*) was studied from 2004 to 2008. The experiment consisted of a control irrigation treatment which was applied at 100% of the crop evapotranspiration (ETc) values for the whole season, and three SDIs imposed as a function of different water-stress index (WSI) values, defined as the ratio of the actual volume of water supply to the ETc rate. The values defined by the WSI were 0.75, 0.65, and 0.50. The plant-water status was measured through the midday stem-water potential (Ψ_{Stem}). Yearly, yield and fruit quality were evaluated at harvest in each treatment, and a global analysis was carried out using the whole dataset. Overall, no significant differences were found in fruit yield between SDIs and control treatments, although significant differences appeared in some of the fruit-quality parameters (total soluble solids and titrable acidity) which also showed significant relationships with integrated stem-water potential (Ψ_{Int}) and irrigation water applied. These findings lead us to conclude that SDIs have important and statistically significant effects on fruit quality. Thus, the application of sustained-deficit irrigation (SDI with WSI of 50) provides promising possibilities for optimising citrus irrigation and boosting the water productivity for citrus orchards in a semiarid Mediterranean climate.

Keywords: *Citrus sinensis*, water-stress index, stem-water potential, irrigation water productivity.

Impacto em longo prazo do déficit de irrigação-sustentada na produtividade e qualidade dos frutos em laranjeira doce cv. Salustiana (SW Espanha)

Resumo

O impacto em longo prazo de diferentes tratamentos de irrigação-sustentada (SDI) em um pomar de laranjas de 13 anos de idade (*Citrus sinensis* L. Osbeck, cv. Salustiana) foi estudado de 2004 a 2008. O experimento consistiu de um tratamento de irrigação controle que foi aplicado a 100% da evapotranspiração de cultura (ETc) para toda a temporada e três SDIs impostas em função de diferentes valores de estresse hídrico (WSI), definidos como a relação do volume real de água requerido com relação à taxa de ETc. Os valores definidos pela WSI foram 0,75, 0,65 e 0,50. O status planta-água foi medido através do potencial de tronco-água a meio-dia (Ψ_{Stem}). Anualmente, a produção e a qualidade dos frutos foram avaliadas no momento da colheita em cada tratamento, e uma análise global foi realizada utilizando o conjunto inteiro de dados. Em geral, não foram encontradas diferenças significativas na produção de frutos entre os SDIs e os tratamentos controle, embora diferenças significativas apareceram em alguns dos parâmetros de qualidade de fruto (sólidos solúveis totais e acidez titulável), que também mostraram relações significativas com potencial tronco-água integrado (Ψ_{Int}) e água de irrigação aplicada. Essas observações levam a concluir que as SDIs têm efeitos importantes e estatisticamente significativos na qualidade dos frutos. Assim, a aplicação do déficit de irrigação-sustentada (SDI com WSI de 50) oferece possibilidades promissoras para otimizar a irrigação de citros e aumentar a produtividade da água para pomares de citros em um clima semi-árido Mediterrâneo.

Palavras-chave: *Citrus sinensis*, indice de estresse hídrico, potencial tronco-água, produtividade da irrigação da água.

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Introduction

In Andalusia (S Spain), citrus trees are grown on approximately 74,000 ha orchards, providing a total yield of about 1.5 million tonnes of fruit (25% of the national production) and consuming around 444 h m^3 of irrigation water per year (Anonimous, 2008).

The most recent forecast for climatic change suggests a significant rise in temperatures and a marked reduction in the annual precipitation during the 21st century, leading to a 17% decrease in the water resources available for agriculture world-wide. Some climatic predictions for 2050 emphase an increase in crop evapotranspiration of more than 20% in the Guadalquivir river basin (S Spain), and these conditions will be even more severe in the westernmost area, where the majority of arable land is concentrated (Rodríguez et al., 2007).

Under such restrictive conditions, it will be crucial to apply different strategies against such stressful climatic conditions, i.e. to reduce water consumption and make more efficient use of water by maximizing water savings and improving its final fruit yield. One of these strategies is deficit irrigation (DI), based on the application of lower amounts of irrigation water than those needed by the crop to compensate for evapotranspiration losses (Fereres & Soriano, 2007).

The DI strategy can reduce the negative effects on crop yield and fruit quality by lowering the evapotranspiration rate to below its maximum level. In this sense, it is important to accurately determine the evapotranspiration level caused by the atmospheric conditions.

On the other hand, any design of DI should take into account the agronomic conditions of the crop, in particular, edapho-climatic conditions, soil management, maximum evapotranspirative-demand periods, and the critical growth periods during which water should not be withheld.

Several authors have reported the advantages of using DI programmes to improve the water fruit yield and fruit quality of citrus trees (Southwick & Davenport, 1986; González & Castel, 1999, 2000; Muriel et al., 2006; García-Tejero et al., 2007, 2008, 2010). The main challenge of DI is to optimise crop production quantitatively as well as qualitatively under water stress, improving the use of limited available water.

The present work examined the response of yield and fruit quality of citrus trees to SDIs applied over four consecutive years, analysing the plant-water status and its relationships with yield and fruit quality under conditions of a limited water supply in a commercial orchard located in SW Spain.

Material and Methods

Experimental site

This study was conducted in a commercial orchard of mature orange trees (*Citrus sinensis*, L. Osbeck, *cv.* Salustiana) grafted on Citrange Carrizo (*Citrus sinensis Osb. x Poncirus trifoliata, Raf.)*, located in the Guadalquivir river basin, SW Spain (37° 44'N, 5° 12' W). Trees were planted 13 years ago, spaced 6 m x 4 m, and were drip irrigated with two pipe lines and eight pressure-compensated emitters per tree at different flow rates, and with a periodicity of three times per week. The average height of the trees was 3.25 m, with a canopy diameter of 4.0 m. The total surface monitored was up to 0.6 ha, which had been subjected to non-tillage practices since the orchard was first planted. The soil surface among tree lines was totally shaded with a natural controlled cover crop (mainly grasses). From October to May this cover was conserved, and mechanically harvested after the trees had been pruned, incorporating the green residues into the soil of the orchard. At the maximum evapotranspirative demand period, the cover crop was chemically removed for avoiding possible competition with the orange trees for available water and nutrients.

The soil at the experimental site is a calcareous sandy-clay loam Typical Fluvisol (FAO, 1998) with 57% sand, 22% silt, and 21% clay. The tree roots were located predominantly at a depth of 0.6 m. The available water-holding capacity was 178 mm m^{-1} on average and the bulk density ranged from 1.23 to 1.30 Mg m^{-3}.

The local climatology is typically dry Mediterranean, with an average annual precipitation of 475 mm, distributed mainly during late autumn to early spring, November to February being the wettest months of the year. Winter temperatures are mild and rarely fall to below 0ºC, and are very high in summer, during July and August, when the maximum temperature often surpasses 40ºC. The annual accumulated evapotranspiration is about 1,600 mm, resulting in an average water deficit of 1,100 mm .

Deficit-irrigation treatments and plant measurements

The experimental design was a randomised complete block with five replicates per treatment. The experimental plot (12 trees) contained three rows with four trees per row. The two central trees were designated for yield and physiological measurements and the remaining as border trees. Analogical water meters were used to measure the volume of irrigation water applied in each treatment.

Three sustained-deficit irrigation (SDI) treatments were applied from 2004 to 2008. These SDIs were derived as a function of the different water-stress index (WSI) values, defined as the ratio of the actual volume of water supply to the crop evapotranspiration rate. The SDIs were as follows: SDI-75 with WSI of 0.75; SDI-65 with WSI of 0.65, and SDI-50 with WSI of 0.50. And a control treatment (C-100) at 100% ET_C in which the trees were irrigated throughout the watering season to provide them with their full water requirement based on ETc calculations. The SDIs and control treatment were implemented from early June to the mid-October (150-283 DOY approximately).

The seasonal values of ETc were obtained through Eq. 1 by Doorembos & Pruitt (1974), with a crop coefficient of 0.7 on average. Climatic data were recorded using an automated weather station located near the orchard, and were compared with the data obtained from a class-A evaporation pan installed in the experimental plot.

$$ETc = \left[\sum_{1}^{7} (ET_o \cdot Kc) - rain \right] \quad \text{(Eq. 1)}$$

where ET_O is the reference evapotranspiration and K_C is the crop coefficient.

Plant measurements

The stem-water potential (Ψ_{Stem}) readings were recorded between 10:00-12:00 h solar time every 10-15 days in two mature leaves per tested tree close to the northern quadrant of the trunk. The integrated stem-water potential (Ψ_{Int}) was calculated according to the modified equation proposed by Myers (1988), which integrates the water potential values with the amount of time during which the trees become stressed:

$$\psi_{int} = \sum_{i=1}^{i=t} \left[\psi_{i+1} \times (n_{i+1} - n_i) + \frac{1}{2}(\psi_i - \psi_{i+1}) \times (n_{i+1} - n_i) \right] \quad \text{(Eq. 2)}$$

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.

At the end of each season, the yield was determined for each individual control tree by weighing the orange fruits with a digital scales with an accuracy of ± 0.01 g and the irrigation-water productivity (IWP), dividing the final yield (kg tree^{-1}) for each treatment by the volume of irrigation water applied.

Fruit-quality characteristics were analysed at harvest in samples from the trees studied (10 fruits per tree) including fruit and rind weight, juice content, and the standard quality parameters: total soluble solids content (TSS) with a thermo-compensated refractometer; titrable acidity (TA) by colorimetric titration with NaOH and phenolphthalein; maturity index (MI) by the ratio of TSS and TA; and equatorial diameter (ED) and polar diameter (PD) with a digital calliper.

Statistical analysis

For each study year, the data were subjected to analysis using a one-way variance (ANOVA; SPSS statistical package; SPSS, Chicago, IL, USA) using Tukey's test for mean separations (P<0.05). Additionally, taking into account the whole dataset, a similar analysis was performed and different correlations between Ψ_{Int} and irrigation water applied were established with the most representative parameters affected by SDI treatments.

Results and Discussion

Water relations and physiological response

The general characteristics of the water balance in the different SDIs and control treatment are presented in Table 1. Irrigation rates in the stressed treatments were close to being a function of ETc as designed, and the volume of water saved using these treatments was up to 50% (SDI-75) and 70% (SDI-65) in relation to the most stressed treatment (SDI-50). The average water savings were some 1,600 m^3 ha^{-1} for SDI-75 and 3,200 m^3 ha^{-1} for SDI-50. The water balance (WB), defined as the difference between total water applied (irrigation + rainfall) and the crop-water evapotranspiration (ETc) was on average close to 45 mm in control trees. In addition, these values for SDI- 75 and SDI-50 were -115 and -274 mm, respectively.

The temporary time course of Ψ_{stem} depended directly on the water volume applied to the crop in each irrigation treatment (Figure 1). Maximum threshold values of –0.6 MPa for Ψ_{stem} were recorded in the control treatment, which was the highest value reached when the water supply was not limited. The seasonal pattern of water status of the plant, as indicted by $\Psi_{stem,}$ in the SDI treatments did not differ markedly from that of control, although the absolute values were directly related with the irrigation applied in each case. Significant differences were found between treatments, especially during the maximum evapotranspirative demand period and these were more evident between the group exposed to the minimum WSI and the control treatment. In this sense, these differences were reflected in the $\Psi_{Int,}$ revealing that the C-100 treatment gave the lowest values, which also were statistically different from those of the more restrictive treatments (Figure 2). Furthermore, the overall analysis showed that, on average, the SDI-75 treatment did not give significantly different results with respect to control, indicating that the value of 90 MPa can be established as a threshold value for the Ψ_{Int}. In this sense, Ψ_{stem} varied on average, between -1.13 MPa for SDI-50 and -0.76 MPa for C-100, being close to -0.99 and -0.84 MPa for SDI-65 and SDI-75, respectively. These findings also suggest that we can save 160 mm of water per year without any significant impact in the water status of the trees. Under these agronomic conditions, even water-stress savings up to 3,000 m^3 ha^{-1} did not promote a limit response in terms of Ψ_{stem} values. In this context, González & Castel (1999) showed that DI treatments with Ψ_{stem} values up to -1.3 MPa did not significantly influence yield in a citrus *cv.* Clementina de Nules. On the other hand, Ψ_{Int} had a significant relationship with the total water supplied for each treatment (r^2 = 0.60), suggesting that this parameter is a good indicator of the plant–water relationship.

Impact of SDIs on yield and fruit quality

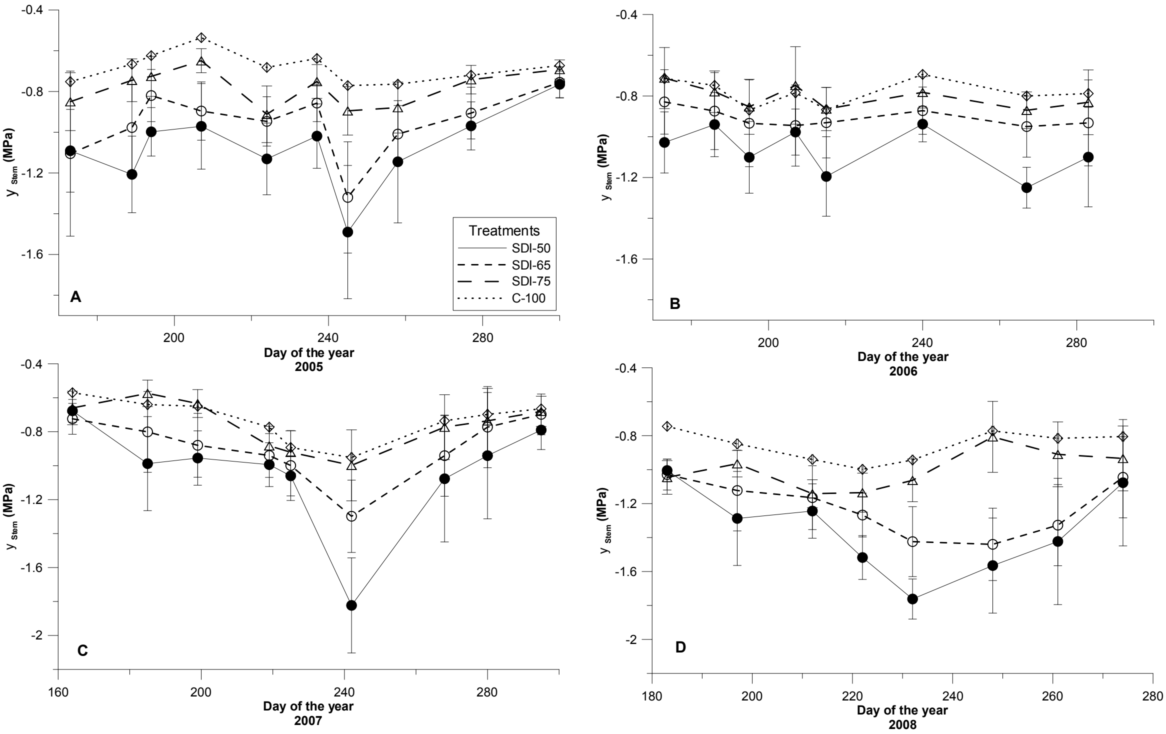

Figure 1. Time course of stem-water potential in each treatment for the study period. SDI, sustained-deficit irrigation

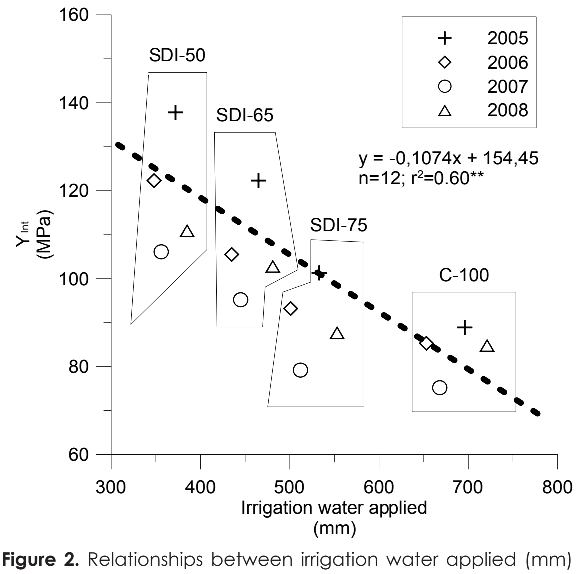

Figure 2. Relationships between irrigation water applied (mm) and integrated stem water potential (Ψ_{int}) for study period. SDI, sustained deficit irrigation. **Significant at P<0.01 level according to Pearson's correlation coefficient.

Table 1. Applied water and water balance for irrigation treatments.

Year	2005	2006	2007	2008
IP[1] (days)	130	170	199	122
Rainfall (mm)	28	119	115	36
ETc (mm)	700	745	641	770
		C-100		
Irrigation (mm)	696	653	668	721
WSI[2]	0.99	0.88	1.04	0.94
WB[3] (mm)	24	27	142	-13
WS[4] (mm)	0	0	0	0
		SDI-75		
Irrigation (mm)	533	501	512	553
WSI[2]	0.76	0.67	0.80	0.72
WB[3] (mm)	-139	-125	-14	-181
WS[4] (mm)	163	152	156	168
		SDI-65		
Irrigation (mm)	465	435	445	481
WSI[2]	0.66	0.56	0.69	0.67
WB[3] (mm)	-207	-191	-81	-253
WS[4] (mm)	231	218	223	240
		SDI-50		
Irrigation (mm)	372	348	356	385
WSI[2]	0.53	0.45	0.56	0.53
WB[3] (mm)	-300	-278	-170	-349
WS[4] (mm)	324	305	312	336

[1] Irrigation Period; [2] Water stress index; [3] Water balance (irrigation + rainfall - ETc); [4] Water Savings (related to C-100); C-100, control at 100 ET_C; SDI, sustained-deficit irrigation

Table 2 lists the yield and commercial fruit-quality parameters during the study years. In 2005, significant differences were found between treatments with regard to fruit weight, total soluble solids (TSS) and titrable acidity (TA). The fruits produced by the SDI-50 treatment were smaller than those in the C-100 treatment. Meanwhile, TA and TSS were higher in the stressed treatments, and especially in the most restrictive treatment. It should be noted that, although the yield response was not statistically significant, it was lower in the most restrictive treatments with a 20% reduction in the fruit crop compared to the C-100 treatment.

During 2006, significant differences were detected between SDIs and control treatments in TSS and TA values, whereas the results for the remainder of the variables were statistically similar. Relevant differences appeared in other parameters such as fruit weight or maturity index, but these could not be considered significant. During 2007, TSS and TA were again the variables most affected by water stress, although during this year, a relative effect of SDIs was found in yield, but could not be considered significant, either.

Finally, during 2008, several effects of SDIs were detected. In this sense, yield, fruit weight, TSS, and TA differed significantly with respect to C-100. This fact is remarkable because during the previous years the main differences were detected in organoleptic properties. This result might indicate an accumulative water-stress situation over the studied years, although, in general, the most relevant effects were detected in the fruit organoleptic properties.

These findings in average terms for the four years showed significant differences between treatments for fruit weight, TSS, and TA (Table 2). It was deduced that water stress caused a significant drop in the fruit weight and an increase in total soluble solids and juice acidity. However, other parameters such as yield or maturity index did not show statistically significant differences between SDIs or control although it is noteworthy that the observed differences were appreciable and that the changes in all these parameters were related to the water deficit undergone by the trees in each treatment.

Taking into account the results related to the effects of SDIs on yield and fruit-quality parameters, significant relationships among

Table 2. Yield and fruit quality under deficit-irrigation strategies for the study period.

Treatment	Yield (kg tree^{-1})	Fruit weight (g fruit^{-1})	Rind (%)	Juice (%)	TSS (°Brix)	TA (g L^{-1})	MI	ED (mm)	PD (mm)
				Season 2004-2005					
SDI-50	88.3a	279.3a	51.6a	44.8a	11.8d	0.92a	12.8a	86.5a	83.6a
SDI-65	100.7a	293.5ab	52.6a	45.2a	11.2c	0.81b	13.9a	87.3a	85.1ab
SDI-75	99.1a	290.7ab	50.7a	46.3a	10.3b	0.80b	12.9a	86.5a	84.6ab
C-100	111.3a	316.9b	52.5a	45.0a	9.6a	0.71b	13.5a	89.3a	88.0b
				Season 2005-2006					
SDI-50	119.6a	203.9a	51.8a	44.6a	11.1c	0.64c	17.3a	76.1a	73.7a
SDI-65	126.7a	207.5a	51.2a	45.6a	10.4b	0.58b	17.9a	76.5a	74.3a
SDI-75	113.9a	206.1a	51.1a	45.1a	9.8a	0.54a	18.1a	75.2a	76.0a
C-100	124.0a	211.8a	51.1a	44.9a	10.1ab	0.59b	17.1a	76.7a	75.5a
				Season 2006-2007					
SDI-50	76.0a	209.6a	48.9a	48.8a	12.5c	1.12b	11.2a	76.6a	70.9a
SDI-65	81.7a	217.5a	48.2a	49.6a	11.7b	1.04ab	11.3a	77.2a	71.7a
SDI-75	82.0a	205.8a	48.2a	49.0a	10.9a	1.03ab	10.6a	75.3a	70.6a
C-100	95.7a	211.9a	49.2a	47.9a	10.6a	0.95a	11.2a	74.8a	70.4a
				Season 2007-2008					
SDI-50	120.5a	120.6a	45.1a	44.4a	11.2b	0.77a	14.5a	68.2a	63.5a
SDI-65	121.4a	131.5ab	43.1a	45.7a	10.5ab	0.76a	13.8a	71.3ab	65.2a
SDI-75	121.1a	155.1c	42.3a	45.4a	9.9a	0.68a	14.6a	73.3b	69.3b
C-100	130.6b	143.0b	43.5a	44.3a	10.0a	0.69a	14.5a	73.0b	67.2ab
				Overall monitoring period 2004-2008					
SDI-50	101.1a	188.6b	49.2a	45.6a	11.6c	0.89b	13.0a	74.4a	70.1a
SDI-65	103.8a	196.1b	48.0a	46.8a	10.9b	0.83b	13.1a	75.7a	71.0a
SDI-75	107.6a	210.5a	47.6a	46.7a	10.1a	0.78a	12.9a	75.9a	73.2a
C-100	115.4a	210.0a	48.3a	45.9a	10.1a	0.78a	12.9a	76.2a	72.7a

C-100, control at 100 ET_C; SDI, sustained deficit irrigation; TSS, Total soluble solids; TA, Titrable acidity; MI, Maturity index; ED, equatorial diameter; PD, polar diameter irrigation water applied and Ψ_{Int} were detected with respect to TA (Figure 3) and TSS (Figure 4). In this context, other parameters such as yield or fruit weight showed a relative relationship, due to the absence of any significant effects of SDIs in these parameters. Thus, conditions causing different levels of water stress in orange trees, will not have any dramatic effect on the yield, but will rather affect other properties which have direct relevance on the final quality of the harvested product. Vélez et al. (2007) were unable to detect any significant differences in either the final production or the fruit weight or in the number of fruits per tree, in response to a DI strategy of cultivation in "Clementine of Nules". As stated by González & Castel (1999) values of stem-water potential must exceed the threshold of -1.3 MPa in order for the effect on the final crop production to be appreciable. Initially this may explain the fact that in the whole dataset, no significant differences were noted in the tree yield between SDIs and control treatment, since the stem-water potential of trees grown under the most water-deprived conditions only erratically exceeded the threshold value.

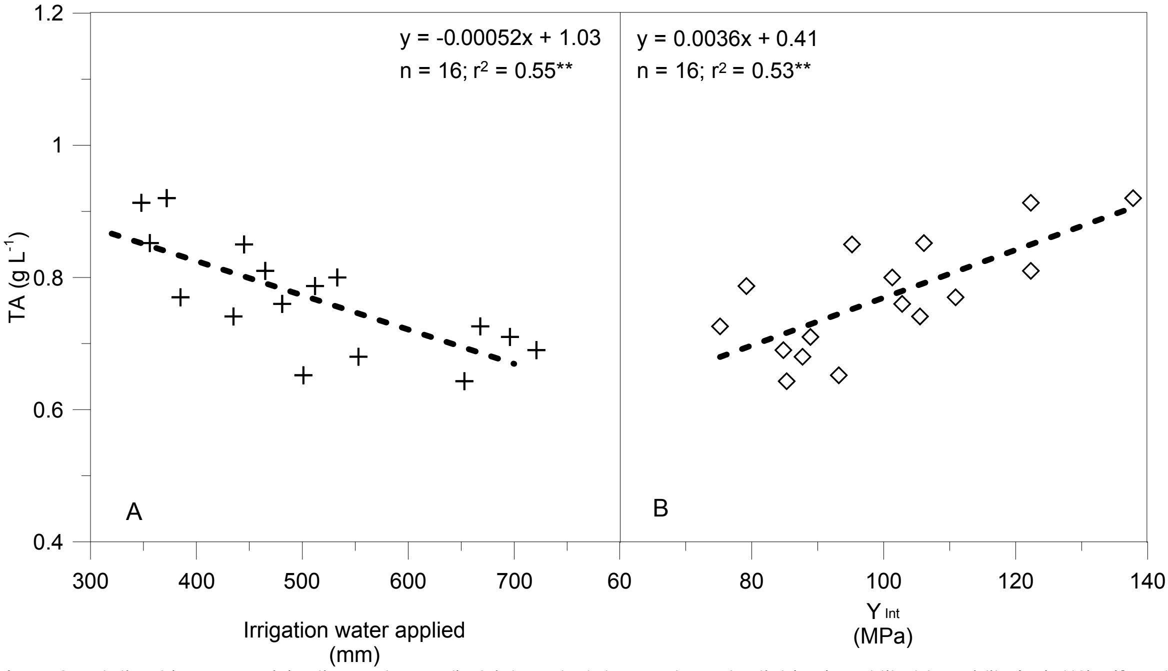

Figure 3. Relationships among irrigation water applied, integrated stem-water potential (Ψ_{Int}) and titrable acidity (TA). **Significant at P<0.01 level according to Pearson's correlation coefficient.

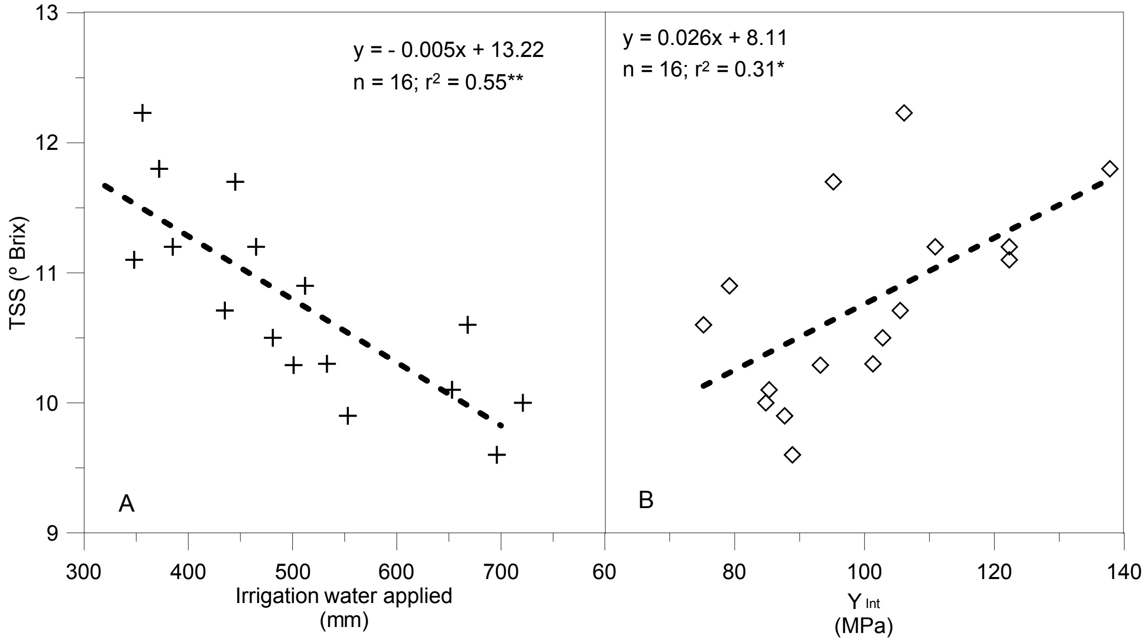

Figure 4. Relationships among irrigation water applied, integrated stem-water potential (Ψ_{Int}) and total soluble solids (TSS). * and ** significant at P<0.05 and 0.01 level according to Pearson's correlation coefficient.

The great importance of the growth periods during which water stress is imposed as well as the different edapho-climatic characteristics of the orchard have been pointed out by such authors as Ginestar & Castel (1996), Castel & Buj (1990), and Treeby et al. (2007) with orange, and Sánchez et al. (1989) with lemon trees. In the present experiment, the SDIs effects were statistically significant for the organoleptic characteristics of the fruit, including TA and TSS. Similar results have been reported by many authors [Ginestar & Castel (1996), González & Castel (1999), Hutton et al. (2007), Vélez et al. (2007), Pérez et al. (2008)]. On the other hand, Yakushiji et al. (1998) showed that water stress leads to an increase in TSS and TA, not a result of dehydration of the fruit, but rather a result of the osmoregulatory response caused by the lack of water (Hockema & Etxeberría, 2001).

SDI and irrigation-water productivity

Average irrigation-water productivity (IWP) ranged from 0.37 to 0.11 kg tree^{-1} mm^{-1} for the SDI-50 and C-100, respectively. Water-productivity data showed a clear linear correlation with the irrigation water applied (r^2 = 0.84) and Ψ_{Int} (r^2 = 0.87) (Figure 5). These results evidence the high capability of SDIs for improving the water-use efficiency in terms of yield and irrigation water. In this sense, the absence of significant differences between treatments on yield caused the highest IWP values to be detected in the most restrictive treatment, in which the irrigation water savings approached 50% in comparison with the control plot.

Increasing IWP may be a means of achieving efficient and effective water use. Climatic conditions in arid and semi-arid world areas such as SW Spain, where available water for irrigated land is the most limiting factor, will force farmers to improve water-use efficiency to maintain profitable crop yields with less water (Ali & Talukder, 2008). Strategies such as DI have shown that water productivity can be enhanced (Ali et al., 2007; Jalota et al., 2006) and could be associated with acceptable commercial production. Today, the low priority given to improving IWP is not doubt related to the low water costs in Mediterranean agriculture areas (Berbel & Gutiérrez, 2004), where water represents only less than 10% of the total production costs, a clear contradiction with the Common Agricultural Policy and the water Framework Directive (García-Vila et al., 2008).

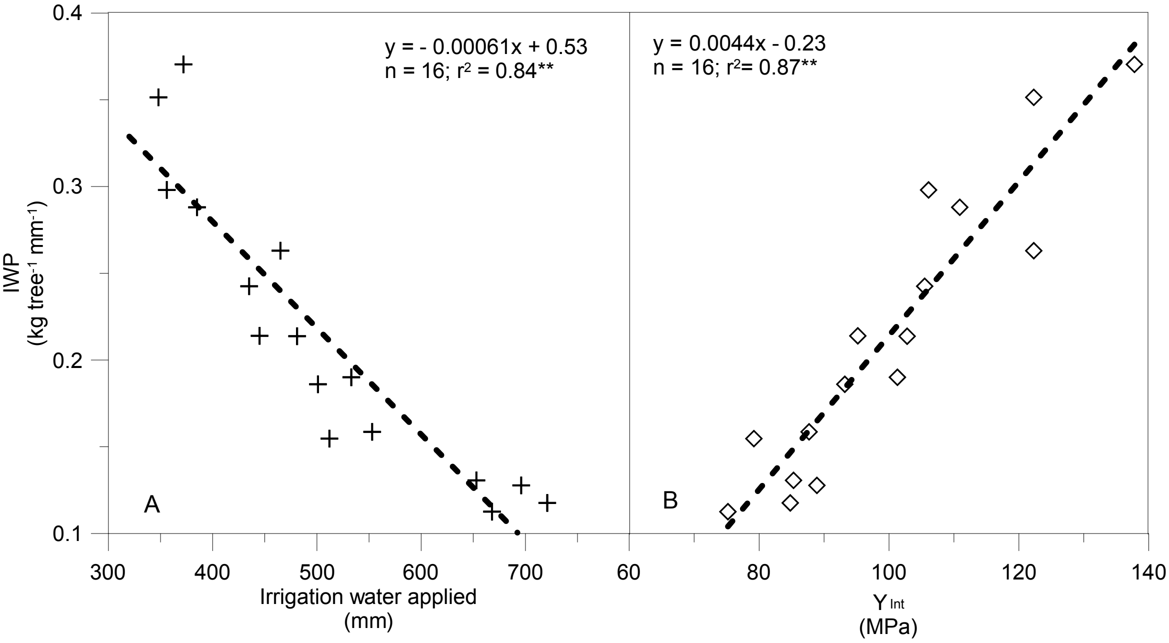

Figure 5. Relationships among irrigation water applied, integrated stem-water potential (Ψ_{Int}), and irrigation-water productivity (IWP). **Significant at P<0.01 level according to Pearson's correlation coefficient.

Conclusions

Conditions causing different levels of water stress in orange trees imposed under our edapho-climatic conditions do not exert a dramatic impact on fruit yield, providing that a threshold value of WSI 0.50 is not surpassed, but rather affect other key factors which have direct relevance to the final quality of the harvested product.

Our results indicate that the main effects of water stress are reflected in organoleptic fruit parameters, such as total soluble solids and titrable acidity, with strong correlations between them and irrigation water applied as well as with Ψ_{Int}. Overall, fruit weight was the morphological variable most affected by water stress, whereas fruit size was not significantly affected during the four study years. Consequently, sustained deficit irrigation, in particular SDI-50 can significantly improve water productivity and might be applied as a long-term strategy under stressful climate conditions or in the case of very high prices of irrigation water. Proper and accurate management of natural and non-renewal resources such as soil and water is considered a blunt tool for social and economic changes.

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