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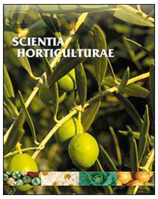

Vegetative and reproductive response of ‘Prime Giant’ sweet cherry trees to regulated deficit irrigation

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ABSTRACT

The agronomic response of sweet cherry (*Prunus avium* L.) ‘Prime Giant’ to a 4 year-long experiment involving deficit irrigation strategies in a Mediterranean climate was studied in a commercial orchard located in the southeast of Spain (Jumilla, Spain). Four drip irrigation treatments were imposed: (i) control treatment (CTL), irrigated without restrictions at 110% of seasonal crop evapotranspiration (ETc); (ii) sustained deficit irrigation (SDI) treatment irrigated at 85% ETc during pre-harvest and post-harvest periods and at 100% ETc during floral differentiation; (iii) regulated deficit irrigation (RDI) treatment irrigated at 100% ETc during pre-harvest and floral differentiation and at 55% ETc during post-harvest, and (iv) farmer treatment (FRM), irrigated according to the farmer’s normal practice. The crop’s response to the different irrigation treatments was analyzed in relation to tree water status. Soil water deficit reduced tree midday stem water potential (Ψ_{stem}), stomatal conductance (gs) and net photosynthesis (Pn). Branch maximum daily shrinkage (MDS) responded rapidly to irrigation changes during pre-harvest and post-harvest. The lowest Ψ_{stem} values were reached by SDI during pre-harvest and by RDI and FRM during post-harvest. RDI did not lead to Ψ_{stem} water potentials falling to below the threshold of -1.6 MPa in any season, although, FRM caused, Ψ_{stem} to fall below -1.8 MPa in 2017.

RDI reduced vegetative growth and did not cause significant lower yields or fruit quality. However, with SDI there was a trend towards smaller fruits and a slightly higher soluble solid content. Post-harvest deficit irrigation increased water productivity without penalizing fruit yield or the quality parameters studied, and allowed water savings of 39% compared to CTL at a time when other fruit tree species require more water. Moreover, RDI and SDI led to significantly less cracking incidence and a lower cracking index, which could extend fruit shelf life.

1. Introduction

Irrigated agriculture has long been and will continue to be the main consumer of water worldwide (UNESCO, 2001). Indeed, 40% of the total world food supply currently depends on the irrigated agriculture, while occupying only 17% of the world’s agricultural land (FAO, 2002). Water is a scarce resource and the development of industry and cities requires increasingly large amounts of fresh water. Thus, there is a constant pressure on irrigated agriculture to conserve water, land and energy, while increasing food and fibre production (Fereres and Evans, 2006). Moreover, agriculture should be prepared to face new challenges such as climate change, which is already modifying water availability worldwide. Irrigation strategies that conserve water resources will be part of the solution to ensure the production of safe food and protection of the environment. Therefore, irrigation management needs to be optimized to increase water use efficiency in agriculture, avoiding the unnecessary waste of this important and limited resource (Saccon, 2018).

Abbreviations: BGR, daily branch growth rate; CTL, control treatment-full irrigation; ET_0, reference crop evapotranspiration; ETc, crop evapotranspiration; FE, fruit efficiency; FRM, farmer treatment; FTI, fruit number per trunk increment; gs, stomatal conductance; IWUE, intrinsic water use efficiency; Kc, crop coefficient; Kr, localization coefficient; LVDT, linear variable differential transformer; MDS, maximum daily branch shrinkage; PFR, photosynthetic photon flux rate; Pn, net photosynthesis; RDI, regulated deficit irrigation; SDI, sustained deficit irrigation; SI_{MDS}, maximum daily branch shrinkage signal intensity; SSC, soluble solids concentration; TCSA, trunk cross-sectional area; VPD, vapour pressure deficit; WP, water productivity; YE, yield efficiency θv soil volumetric water content referred to field capacity; Ψm, soil matric potential; Ψ_{stem}, midday stem water potential

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One of the most promising avenues for improving water productivity in certain plant species is the use of regulated deficit irrigation (RDI) strategies. Chalmers et al. (1981) defined regulated deficit irrigation as a strategy which consists of reducing water supplied to the crop during specific phenological stages to manage crop vegetative growth and improve water efficiency without penalizing fruit yield or quality.

RDI effects on tree crops such as nectarine, peach and apricot have been studied, and the results indicate that yield, fruit size and fruit quality can be maintained with water savings of around 40% (de la Rosa et al., 2015; Girona et al., 2005; Pérez-Pastor et al., 2009; Torrecillas et al., 2000). However, when drought stress is excessive or is applied at the wrong moment, both yield and fruit size are affected as has been reported in plum and apricot (Intrigliolo and Castel, 2006; Torrecillas et al., 2000). There is limited information on the response of sweet cherry to drought and deficit irrigation strategies (Dehghanisanij et al., 2007; Livellara et al., 2011; Marsal et al., 2009, 2010; Nieto et al., 2017). Moreover, there is an even greater scarcity of information about the effects of RDI on long term yield, fruit quality and vegetative growth of sweet cherry in Mediterranean conditions.

RDI in stone fruits usually involves applying deficit irrigation during stage II of fruit development (pit hardening). However, in sweet cherry and in early cultivars of prune trees such as ‘Flanoba’ nectarine, whose fruit develops rapidly, stage II is indistinguishable and overlaps stage I and III. For this reason, it is not recommendable to apply water deficit at any stage of fruit growth in early and extra early cultivars including sweet cherry trees (de la Rosa et al., 2015; Marsal, 2012).

Sweet cherry (*Prunus avium* L.), a non-climacteric stone fruit of the genus Prunus, is held in high regard by consumers, due to its organoleptic and nutritional characteristics, and by growers because of the good returns it provides. Worldwide production of fresh cherries has increased by 35% in the last 20 years, reaching 2.2 Mt (Tricase et al., 2017) with Spain the 5th greatest producer (FAOSTAT - Food and Agriculture Organization of the United Nations Statistics Division, 2015). Sweet cherry has been described as being highly sensitive to water deficit during pre-harvest. Nevertheless, despite the frequency of summer droughts in the Mediterranean Basin, there is a lack of information on the effect of deficit irrigation on the physiological and agronomical response of sweet cherry trees (Centritto, 2005).

The objective of this work was to study the effects of different deficit irrigation strategies on the water status, yield and vegetative growth of adult ‘Prime Giant’ sweet cherry trees in order to optimise irrigation water management in a semiarid area with scarce water resources.

2. Materials and methods

2.1. Site description

The experiment was conducted at a 0.5 ha commercial orchard located in Jumilla (Murcia, Spain, 38° 8′ N; 1° 22′ W, altitude 670 m) from 2015 to 2018. The area has a typical semi-arid Mediterranean climate characterized by wet mild winters and hot dry summers. The soil is moderately stony, the texture sandy loam with a particle size distribution of 67.5% sand, 17.5% silt and 15% clay, with a high level of assimilable phosphorus (108.67 mg kg^{-1}) and an adequate exchangeable potassium (3.2 mmol kg^{-1}) content. The irrigation water, which comes from a well, had an average electrical conductivity ($EC_{25°C}$) of 0.8 dS m^{-1}, with maximum concentration of sodium and chloride of 1.7 and 1.05 mmol L^{-1}, respectively.

2.2. Experimental design and treatments

The study was carried out in fifteen year-old mature sweet cherry trees (*P. avium* L. ‘Prime Giant’) grafted on SL64 rootstock and ‘Early Lory’ and ‘Brooks’ as pollenizers, at a plant density of 667 trees ha^{-1}. Drip irrigation consisted of a single drip line per tree row and three pressure-compensated emitters per tree of 4 L h^{-1} each. Fertilization was the same for all treatments and regardless of the water applied. The fertilization programme applied consisted of 63, 30, 107 and 8 kg ha^{-1} of N, P_2O_5, K_2O and CaO, respectively, in the drip irrigation water with the aim of re-establishing the levels of nutrients taken up by mature sweet cherry trees. Fertilization, pruning, weed and pest control were the same for all trees and were consistent with local management practices. The irrigation was applied during the dry period, from March before flowering until November. Full bloom was in April, and annual pruning was carried out in August (approximately 60 d after harvesting).

The experiment involved four irrigation treatments: (i) a control treatment (CTL) irrigated to satisfy maximum crop evapotranspiration (ETc) throughout the growing season (110% ETc); (ii) a sustained deficit irrigation treatment (SDI), irrigated at 85% of ETc during pre-harvest and post-harvest except for the 15–20 days after the first harvest (floral differentiation), when trees were irrigated at 100% ETc; (iii) a regulated deficit irrigation treatment (RDI), irrigated at 100% of ETc during pre-harvest and the first 15–20 days of flower differentiation and 55% of ETc during post-harvest (a non-critical period), and (iv) farmer treatment (FRM), irrigated according to the farmer’s normal practice which consists of irrigating above the crop water requirements during pre-harvest and applying uncontrolled water deficit during post-harvest.

Crop evapotranspiration under drip irrigation (ETc) was estimated using the equation: $ETc = ET_0 \times Kc \times Kr$, where ET_0 is the average value of the evapotranspiration during the 3–5 days prior to applying the new irrigation scheduling, Kc is a crop-specific coefficient based on Marsal (2012), which varies from 0.3 in March and November to 0.96 in June and July, and Kr is a localization factor based on Fereres et al. (1982) and related to the percentage of ground covered by the crop (Kr = 0.90).

2.3. Meteorological conditions

Daily climatic data such as air temperature, air relative humidity, rainfall and crop reference evapotranspiration were recorded by an automatic weather station near the experimental orchard owned by the Spanish agroclimatic information service (SIAR; http://crea.uclm.es/siar/datmeteo/). From the temperature and humidity data, the vapour pressure deficit (VPD) was calculated according to Allen et al. (1998).

2.4. Soil water status

Soil volumetric water content, was obtained with two FDR sensors (Enviroscan, Sentek Pty. Ltd., Adelaide, Australia) per replicate at 20 and 40 cm depth located 0.23 m from the emitter and 1.5 m from the trunk of the central tree of each block, under the canopy shade. The daily minimum value of the soil volumetric water content is referenced to field capacity as a percentage of the maximum soil water content available in the soil (θv, %). Likewise, the matric potential of the soil (Ψm, kPa) was measured in one tree per replicate by means of two thermal compensation capacitive sensors (MPS-6, Decagon Devices Inc., Pullman, WA, USA) at 25 and 50 cm depth and at a distance of 0.23 m from the emitter. The mean value of Ψm from 11:00 to 14:00 h (solar time) was calculated.

2.5. Plant water status

The plant water status was monitored approximately every ten days by measuring stem water potential at noon (Ψ_{stem}; MPa) with a Scholander pressure chamber (Model 3000, Soil Moisture Equipment, Santa Barbara, CA, USA), according to the methodology proposed by McCutchan and Shackel (1992) in 6 trees per treatment equipped with linear variable differential transformer (LVDT) sensors. The mature and healthy leaves selected were from the north quadrant close to the trunk, thus avoiding solar exposure. Leaves were enclosed in black polyethylene bags and covered with aluminium foil at least 2 h before measurement. Likewise and also at noon, gas exchange measurements were measured in four sun-exposed leaves of the outer canopy per replicate. Maximum stomatal conductance (gs; mmol m^{-2} s^{-1}) and net photosynthesis (Pn; µmol m^{-2} s^{-1}) were measured at a photosynthetic photon flux density of 1500 µmol m^{-2} s^{-1}, near constant ambient CO$_2$ concentration ($\approx$380 µmol mol^{-1}) and leaf temperature ($\approx$25 °C) using a portable gas exchange system CIRAS^{-2} (PP Systems, Hitchin, Hertfordshire, UK). Intrinsic water use efficiency (IWUE) was calculated as the ratio between Pn and gs (µmol mol^{-1}).

Branch diameter fluctuations were recorded by two dendrometers (LVDT sensors, model DF ± 2.5 mm, accuracy ± 10 µm, Solartron Metrology, Bognor Regis, UK) per replicate, each placed on a main tree branch away from direct sunlight. The sensors were installed on aluminium and invar holders to prevent thermal expansion. LVDT measurements were performed in differential input configurations. The maximum daily branch shrinkage (MDS) was calculated as the daily difference in diameter between the maximum and the minimum. MDS signal intensity (SI$_{MDS}$) was calculated by taking the ratio of each treatment versus CTL (SI$_{MDS}$ = MDS$_{TREATMENT}$ / MDS$_{CTL}$). SI$_{MDS}$ is a dimensionless variable, where one (unity) is equivalent to the absence of water deficit and values above one indicate plant water deficit (Goldhamer and Fereres, 2001). Daily branch growth rate (BGR) was calculated as the difference in diameter between the maximum of two consecutive days (Goldhamer and Fereres, 2001).

Branch diameter fluctuations, matric potential and volumetric water content measurements were recorded every 30 s and the datalogger was programmed to report means every 10 min. Two replicates per treatment were equipped with a wired platform of one datalogger and two multiplexers (Campbell Scientific, Logan, UT, USA) while the other two replicates used a ZigBee wireless sensor network (Widhoc Smart Solutions SL, Fuente Alamo, Murcia, Spain) configured in a star topology (Morais et al., 2008). Data access was by WIFI radio-link provided by a local internet supplier.

2.6. Vegetative growth

Vegetative growth was measured as pruning wood, canopy volume, shaded area, cumulate shoot growth and trunk cross-sectional area. The pruning wood was expressed as the fresh mass (kg tree^{-1}) of the amount of pruned wood per tree each year individually weighed in the field. Canopy volume was annually calculated before pruning according to Hutchison (1978) based on canopy height and diameters (across and within rows) of the five central trees of each replicate. Likewise, the shaded area of the same trees was estimated in CTL, RDI and SDI as light intercepted at noon on completely clear days, when photosynthetic photon flux rate (PFR) was close to 1500 µmol m^{-2} s^{-1}. PFR interception was calculated from 30 measurements corresponding to a grid (0.25 m^2 mesh) that covered half of the tree spacing, using a linear ceptometer with an 80 cm long probe (Accupar Linear PAR, Decagon Devices Inc., Pullman, WA, USA) on the soil surface. Cumulate shoot growth was measured in 4 marked current season shoots per tree, 2 trees per replicate each month with a tape measure (Tylon Pocket, Stanley, New Britain, CT, USA) in 2016 and 2017. At the beginning, at harvest and at the end of the growing season, trunk diameter of all trees was measured with a tape measure (Pi meter MF612 A, Weiss, Erbendorf, Germany). The measurements were always taken in a marked location in the trunk, at 0.20 m from the soil surface in the five central trees per replicate. Trunk cross-sectional area (TCSA) was estimated as the circle area from the trunk diameter measured.

2.7. Yield

At harvest (June 3rd and 10th in 2015, 17th and 22nd in 2016, 2nd in 2017 and 14th and 19th in 2018), fruits from 5 central trees of each replicate were harvested and weighed. The individual yield of each tree was weighed to determine yield per tree. Similarly, at harvest, fruits were counted in 5 kg samples in order to calculate the unitary mass of the cherries. Double and cracked fruits in the sample were also counted in order to measure their proportion in the total yield. The number of fruit per tree was estimated from fruit unitary mass and yield per tree. Moreover, soluble solids concentration (SSC; %) was measured from 10 fruits per replicate with a refractometer (N1, Atago, Tokyo, Japan). With the aim of assess if irrigation treatments can affect fruit susceptibility to crack, cracking index was measured from the fruits harvested in 2018 following the procedure described by Christensen (1972). 50 fruits per replicate, four replicates per treatment, were immersed in 2 L distilled water (pH 7) at 20 °C. Cracks presence on the fruit was evaluated after 2, 4 and 6 h. At each time, cracked cherries were removed and recorded. Cracking index was calculated as: Cracking index = $100 \times [5a + 3b + c] \times (250)^{-1}$. In this equation a, b and c represent the number of cracked fruits at 2, 4 and 6 h of immersion, respectively.

2.8. Statistical analysis

The experimental layout was a completely randomized block design with four replicates per treatment. Each replicate consisted of seven trees: the five central trees were used for measuring the yield and pruning wood per tree, while only the two central trees were used to monitor water relations, the other trees serving as guard trees. Analysis of variance (ANOVA) was performed using the statistical software packages IBM SPSS Statistic 24 (IBM Corp., Armonk, NY, USA) and Statgraphics centurion XVI (StatPoint Technologies Inc., The Plains, VA, USA) to determine the effect of the different irrigation treatments on soil and plant indicators, vegetative growth and yield. Means were separated by a post-hoc test (Duncan's multiple range) with a significance level of $P < 0.05$. Linear relationships as well as regression analysis between variables were calculated with SigmaPlot 12.5 (Systat sofware Inc., San Jose, CA, USA).

3. Results

3.1. Meteorological conditions and irrigation water applied

The reference crop evapotranspiration (ET$_0$) showed a similar seasonal evolution all the years of the study (2015–2018), with an annual average sum of 1256 mm, with a maximum in June and July and mean values higher than 5.0 mm d^{-1} and daily peaks of 7.0 mm d^{-1} occurring in mid-late June. Precipitation was not sufficient to satisfy the demand of the crop's evapotranspiration varying from 260 to 360 mm. In 2015, precipitation was 129 mm during the growing season (April – September), which represented 49% of the annual total. This proportion changed in 2016 and 2017, when 142 and 84 mm of rain fell, representing 38 and 39%, respectively. During the pre-harvest period (April – June) of 2018, the rainfall recorded was higher than the rainfall measured during the three previous years for the whole growing season (264 mm). The daily maximum vapour pressure deficit (VPD) during the growing season showed a similar pattern to ET$_0$, with a VPD average of 1.6 kPa. The maximum annual values were always recorded in July, with the maximum VPD registered (4 kPa) on DOY 188 in 2015.

During 2015 pre-harvest, a hail storm (139 DOY) partially damaged the fruit and negatively affected the commercial yield. In 2018, 11 d before the first harvest, a rainy spell of 7 d (86 mm of rain) affected fruit quality. The occurrence of precipitation during the 2018 pre-harvest reduced the atmospheric demand in 2018 and consequently diminished the total water supplied (Table 1), although the pre-harvest period lasted longer than in the previous years.

Table 1 presents the irrigation water applied to each treatment and in each period (pre-harvest, floral differentiation and post-harvest) from 2015 to 2018. It can be seen that RDI saved the greatest amount of water (39%) compared with CTL over the whole experiment, while SDI

Table 1
Irrigation water applied ($m^3\,ha^{-1}$) during each period, pre-harvest (Pre), floral differentiation (Floral Diff) and post-harvest (Post) of the experimental period 2015–2018 to 'Prime Giant' sweet cherry trees exposed to four different irrigation treatments, control (CTL), sustained deficit irrigation (SDI), regulated deficit irrigation (RDI) and a treatment based on normal farming practices (FRM).

		Irrigation water applied ($m^3\,ha^{-1}$)			
		CTL	SDI	RDI	FRM
2015	Pre	1977	1629	1717	2522
	Floral Diff	570	561	567	421
	Post	4369	3114	1820	3336
	TOTAL	**6916**	**5304**	**4104**	**6279**
2016	Pre	2143	1527	1909	2689
	Floral Diff	666	635	640	539
	Post	4221	2668	1677	2889
	TOTAL	**7030**	**4830**	**4226**	**6117**
2017	Pre	1904	1379	1664	2189
	Floral Diff	673	662	661	539
	Post	4324	3091	2091	2954
	TOTAL	**6901**	**5132**	**4416**	**5682**
2018	Pre	1978	1405	1760	2201

and FRM saved 28% and 15% respectively, of the water applied to CTL.

3.2. Soil water status

The seasonal trends in soil water matric potential (Ψm) and soil water content (θv) distinguished between the different irrigation strategies imposed in the three irrigation phases every year of the study. Ψm mean values at 25 and 50 cm depth were similar during pre-harvest in CTL, FRM and RDI treatments (between -10 and − 30 kPa; Table 2) and all were higher than in SDI treatment (between -30 and − 130 kPa; Table 2). During the first days of post-harvest (floral differentiation), there were no differences among treatments. Once the irrigation deficit was imposed in RDI and SDI treatments, differences appeared, and each treatment was significantly different.

As in the case of Ψm, θv showed significant differences among treatments during post-harvest all years of the study. The FRM treatment showed a significantly lower θv value during 2017 floral differentiation, indicating that FRM changed its irrigation regime. The mean θv value in CTL treatment remained in a close range (between 98 and 84% at 20 cm depth and 93 and 82% at 40 cm), while RDI was clearly influenced by irrigation changes (average of 88% and 56% during pre-harvest and post-harvest, respectively, Table 3).

3.3. Plant water status

3.3.1. Midday stem water potential

Midday tree water status was affected by irrigation treatment every year of the study. In the pre-harvest periods of 2015 and 2017, SDI trees resulted in significantly lower Ψ_{stem} than controls at all measurement times, except the first one; however, in 2016 and 2018 there were hardly any differences between treatments until just before harvest (Fig. 1).

As was to be expected, when the evaporative demand increased, all treatments, including CTL, exhibited a trend to lower values than during pre-harvest, however the steepest drop in Ψ_{stem} occurred in RDI and FRM in response to the deficit in soil water content following the irrigation treatments imposed. The reduction in Ψ_{stem} was clear between DOY 180 and DOY 240 (end June – early August), a change that occurred in parallel with the decrease in the soil water content (Fig. 1, Table 2). During 2017 post-harvest, the general seasonal trend of Ψ_{stem} was characterized by a steady, but more marked reduction, RDI trees resulted in Ψ_{stem} below -1.3 MPa at two consecutive measurement points. Similarly, Ψ_{stem} of FRM trees led to -1.8 MPa, which was the

Table 2
Mean value of soil water potential (Ψm) at 25 and 50 cm depth to each irrigation period, pre-harvest (Pre), floral differentiation (Floral Diff) and post-harvest (Post) of the experimental period 2015–2018 to 'Prime Giant' sweet cherry trees exposed to four different irrigation treatments, control (CTL), sustained deficit irrigation (SDI), regulated deficit irrigation (RDI) and a treatment based on normal farming practices (FRM).

		Ψm 25 cm (kPa)									Ψm 50 cm (kPa)								
		CTL		SDI		RDI		FRM		ANOVA	CTL		SDI		RDI		FRM		ANOVA
Pre	2015	−11.27	a	−22.27	b	−10.36	a	−9.49	a	⁎⁎	−16.14	a	−50.22	b	−23.09	ab	−11.22	a	⁎
Floral Diff		−11.65		−9.51		−12.10		−18.61		n.s.	−16.22		−16.17		−21.29		−20.42		n.s.
Post		−22.98	a	−93.90	a	−206.14	b	−90.23	a	⁎	−29.61	a	−148.32	ab	−394.49	c	−280.75	bc	⁎⁎
Pre		−11.07		−30.62		−10.99		−10.54		n.s.	−14.02		−52.82		−15.49		−11.82		n.s.
Floral Diff	2016	−12.17		−14.21		−11.84		−8.92		n.s.	−21.41		−14.37		−33.06		−12.98		n.s.
Post		−22.53	a	−188.42	bc	−273.77	c	−72.99	ab	⁎	−33.47	a	−211.28	b	−374.83	c	−272.91	c	⁎⁎⁎
Pre		−11.81	a	−61.22	b	−14.10	a	−14.91	a	⁎⁎	−22.76	a	−195.74	b	−47.91	a	−24.90	a	⁎⁎
Floral Diff	2017	−10.02		−13.56		−10.03		−163.59		n.s.	−14.11		−42.63		−21.05		−75.63		n.s.
Post		−34.39	a	−146.67	a	−335.85	b	−147.29	a	⁎	−36.58	a	−236.34	b	−442.92	c	−404.76	bc	⁎⁎
Pre	2018	−12.93	a	−39.28	b	−14.58	a	−10.64	a	⁎	−15.43	a	−114.85	b	−19.83	a	−10.98	a	⁎⁎

Each value is the mean of the 4 replicates. Mean values within the same period (row) followed by a different letter denote significant differences among treatments according to Duncan multiple range test ($P < 0.05$). In the ANOVA column, ⁎, ⁎⁎, ⁎⁎⁎ refer to significant effect at $P = 0.05$, 0.01 or 0.001 respectively and n.s. to not significant.

Table 3
Mean value of soil water content referenced to field capacity (θv) at 20 and 40 cm depth to each irrigation period, pre-harvest (Pre), floral differentiation (Floral Diff) and post-harvest (Post) of the experimental period 2015–2018 to 'Prime Giant' sweet cherry trees exposed to four different irrigation treatments, control (CTL), sustained deficit irrigation (SDI), regulated deficit irrigation (RDI) and a treatment based on normal farming practices (FRM).

		θv 20 cm (%)									θv 40 cm (%)								
		CTL		SDI		RDI		FRM		ANOVA	CTL		SDI		RDI		FRM		ANOVA
Pre		92.81		84.00		92.16		93.31		n.s.	86.41		68.70		85.00		88.40		n.s.
Floral Diff	2015	92.73		89.15		94.90		92.00		n.s.	88.00		82.73		90.87		90.57		n.s.
Post		84.33	a	68.88	a	56.90	b	68.91	a	⁎	82.20	a	72.89	a	58.97	b	69.65	a	⁎
Pre		95.28		86.64		91.25		94.01		n.s.	87.45		72.41		75.69		88.25		n.s.
Floral Diff	2016	98.30		86.63		96.65		93.43		n.s.	93.29		82.43		82.01		91.18		n.s.
Post		94.10	a	75.68	ab	57.47	b	61.40	b	⁎	88.47	a	67.01	b	61.55	b	67.11	b	⁎
Pre		90.72	a	71.96	b	88.94	a	90.98	a	⁎⁎	84.44	a	59.83	b	87.88	a	84.28	a	⁎
Floral Diff	2017	90.52	a	87.08	a	90.40	a	72.42	b	⁎⁎	82.80	a	70.04	ab	88.02	a	65.06	b	⁎⁎
Post		89.45	a	77.24	b	53.33	c	59.53	c	⁎⁎	85.95	a	67.60	ab	53.21	b	57.70	b	⁎⁎
Pre	2018	91.98	a	74.45	b	89.69	a	94.34	a	⁎	85.56	a	68.07	b	90.15	a	92.02	a	⁎⁎

Each value is the mean of the 4 replicates. Mean values within the same period (row) followed by a different letter denote significant differences among treatments according to Duncan multiple range test ($P < 0.05$). In the ANOVA column, ⁎, ⁎⁎ refer to significant effect at $P = 0.05$ or 0.01, respectively and n.s. to not significant.

absolute minimum value measured throughout the experiment. At harvest, the Ψ_{stem} of SDI trees was -0.7 MPa every year of the study, which was between 0.14 and 0.20 MPa lower on average than in CTL trees for 2015–2018, with significant differences (Fig. 1).

3.3.2. Leaf gas exchange

During the 2015, 2016 and 2017 post-harvest periods, significant differences were detected for CTL and RDI in Pn and gs. Based on the results of stomatal conductance, gs was significantly higher in CTL trees during post-harvest than in RDI trees (196 and 110 mmol m^{-2} s^{-1}, respectively). Post-harvest net photosynthesis also differed significantly between CTL and RDI trees every year of the study. During post-harvest, Pn pointed to statistically significant differences between CTL and SDI in 2016 and 2017, while gs showed no such difference since Pn showed less variability than gs between measurements within the same treatment (Table 4).

During pre-harvest, despite the differences in the water supplied by irrigation to each treatment, trees from all treatments resulted in similar gs and Pn. Stomatal conductance at the floral differentiation stage of 2017 identified statistical differences between FRM and the rest of the treatments, which agreed with the significantly lower soil water content and lower Ψ_{stem} compared with the other treatments (Table 4).

IWUE was higher in deficit treated trees than in controls. In 2015 pre-harvest all trees resulted in similar IWUE; however in 2016, 2017 and 2018 SDI trees turned out in higher IWUE than CTL trees but without significant differences. In post-harvest, RDI trees had an IWUE that was 30 and 23% higher than that measured in CTL and SDI trees, respectively, and, during post-harvest 2015, RDI trees were significantly more efficient in the use of water than all the other trees (Table 4).

3.3.3. Branch diameter fluctuations

The seasonal evolution of the MDS and BGR showed different results according to the irrigation treatment imposed. SDI trees recorded pre-harvest MDS values higher than 400 μm, while well-watered plants of the other treatments showed values close to 200 μm. During post-harvest, maximum MDS values were recorded in all the treatments in July. RDI produced the greatest fluctuations, higher than 600 μm, and CTL trees reached fluctuations of 320 μm. MDS of FRM trees was similar to the trees under RDI but not on the same dates (Fig. 2). The pre-harvest, floral differentiation and post-harvest means of SI_{MDS} in SDI trees were 1.3, 1.05 and 1.3, in RDI trees were 1.1, 1.05 and 1.6; and in FRM trees were 0.9, 1.2 and 1.5, respectively. In the 2017 post-harvest period, RDI trees showed a higher SI_{MDS} than in previous years, values reaching 1.8 at the end of July and early August. In the same vein, FRM led to a higher mean SI_{MDS} value of 1.9 in 2017, even exceeding 3.0 during midsummer.

At the end of the experiment, the different irrigation treatments were seen to have induced clear differences in the branch growth rates of the trees. BGR showed sigmoid patterns each year of the study, with rapid vegetative growth that coincided with flower and fruit development in the tree (from March to June), slower growth from June to September, and no growth the rest of the season (October onwards). Mean seasonal branch growth in control trees was about 4.3 mm. Trees of deficit irrigation treatments resulted in a similar pattern but less pronounced, the BGR of the trees under SDI and RDI was 26 and 35% lower than that measured in CTL trees. During pre-harvest 2015 and 2017, BGR of trees was not significantly different among treatments; however, during 2016 and 2018 differences appeared, and SDI trees resulted in a significantly lower BGR than those from CTL (Fig. 2). The post-harvest irrigation deficit applied in RDI trees caused sharp decrease in its BGR. Deficit irrigation imposed during post-harvest in RDI trees resulted after 10 d in a BGR reduction from 39 to 9 μm d^{-1}. Meanwhile, control trees remained BGR close to 35 μm d^{-1}.

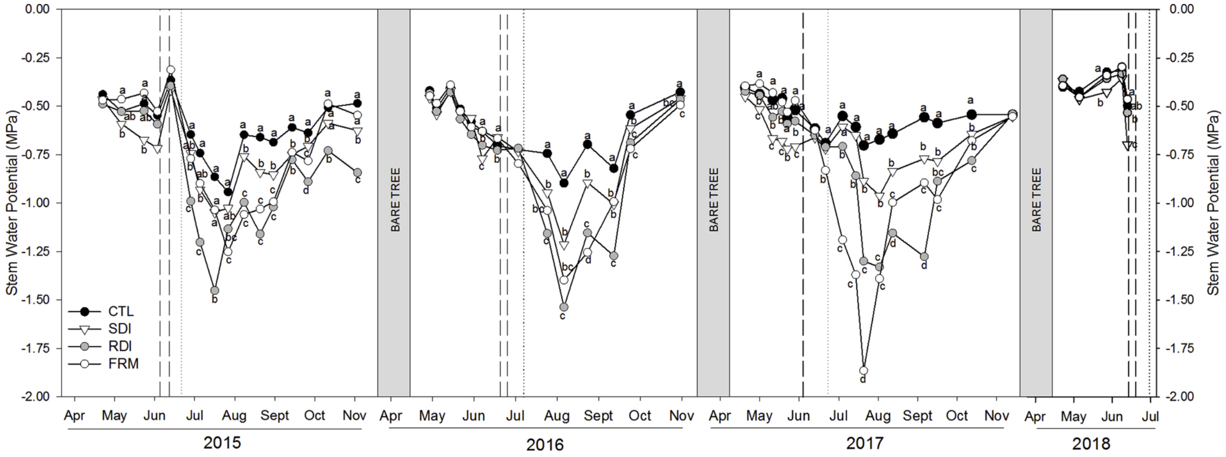

Fig. 1. Evolution of the midday stem water potential (Ψ_{stem}) during the experimental period 2015–2018 of 'Prime Giant' sweet cherry trees exposed to four different irrigation treatments, control (CTL, black circles), sustain deficit irrigation (SDI, triangles), regulated deficit irrigation (RDI, grey circles) and a treatment based on normal farming practices (FRM, white circles).
Vertical dashed lines show harvest days and dotted line the start of the postharvest deficit period. Each point is the mean value of 6 measurements. Different letters on the same day denote significant differences among treatments, according to Duncan multiple range test ($P < 0.05$).

3.4. Vegetative growth

Different irrigation strategies did not lead to significant differences in the tree's vegetative growth for the first two years of the experimental period except shoot length. Tree's TCSA was not significantly affected by irrigation treatments any year of study. On the other hand, tree's pruned wood was significantly different among trees of different irrigation treatments (Table 5). In general, CTL trees increased their vegetative growth as the experiment progressed. RDI trees resulted in the lowest canopy volume in the last measurement of the experiment, and consequently, lower PFR interception and lower shaded area. Thus, in the last year of the study RDI trees had a significantly lower shaded area than CTL trees. Shoot length reached greater average values in the third year of the study in all the treatments, but especially CTL in which it coincided with a bigger pruning mass that year.

3.5. Yield and double and cracked fruits

There was no significant effect of irrigation on yield parameters (Fig. 3A and B). In 2015 and 2017, fruit yield and number of fruits per tree (Fig. 3B) were lower than in 2016 and 2018 in all treatments (with 23.5, 43.4, 29.6 and 40.3 kg tree^{-1} for CTL trees each year of the study). It should be remembered that in 2015 as a result of a hail storm, 11% of that year's commercial yield was damaged and could not be harvested. Consequently, fruit unitary mass was higher in 2015 and 2017 than in 2016 and 2018 and fruit size distribution resulted in greater proportion of fruits of SDI in the lowest categories, but with no differences among treatments (Figs. 3C and 4). Thus, high cropping years showed lower fruit unitary mass. A linear relationship was obtained between the total yield and the fruit unitary mass: [Unitary mass (g) = -0.1021 Yield (kg tree^{-1}) + 13.67. (r^2 = 0.67)].

There were no significant differences in fruit SSC among treatments, although the deficit irrigation treatments tended to induce higher values, especially SDI, which, at the last harvest, led to average fruit SSC values that were 10% higher than that of controls (Fig. 3D). The frequency of double fruit was not influenced by the irrigation treatment and there were no significant differences due to this effect; the occurrence of double fruit varied from 1.5 to 13% of the total fruit harvested from year to year, depending on environmental conditions (Table 6).

Cracking incidence of cherries was not significantly different among treatments in 2017, a year in which, in the month prior to harvest, a rainfall episode of 11 mm caused percentage of cracking to reach 1% of the total fruit. In 2018, eleven days before harvest, several rain episodes took place with a total amount of 86 mm over seven days, and, depending on the treatment from 9 to 23% of the fruit cracked (Table 6). Cherries of CTL and FRM had a similar cracking incidence of close to 20% although SDI at the first harvest and both deficit treatments at the second harvest resulted in significantly less cracked fruit. These results agree with the cracking index determined in the laboratory, which was significantly higher in CTL and FRM cherries.

3.6. Water productivity

The productive efficiencies varied according to the irrigation imposed in each treatment. RDI trees resulted in higher water productivity (WP, calculated as the ratio of yield to irrigation water applied) than the trees of the other irrigation treatments, reaching 5.3 kg m^{-3} in 2017, doubling the productivity of CTL trees (Table 7). Moreover, RDI trees tended to produce a greater number of fruits per trunk cross sectional area (fruit number efficiency, FE), and a greater number of fruits per increment of the trunk cross sectional area (fruit number per trunk increment, FTI). Furthermore, in 2018 RDI trees lead to significant higher yield efficiency (YE, ratio of yield to trunk cross sectional area) than controls (Table 7). Trees under RDI resulted in higher water productivity than the trees of any treatment every year of the study in spite of variations in yield. Trees under SDI also resulted in significant higher WP than those of CTL. However, these differences were not accompanied by differences in fruit and yield efficiency.

4. Discussion

The results of this study show that sweet cherry 'Prime Giant' seems to be sensitive to deficit irrigation during the pre-harvest period more than that post-harvest. The irrigation restrictions applied in RDI led to a statistically significant lower mean soil matric potential and soil water content than in CTL after harvest in this study (Tables 2 and 3). Moreover, SDI treatment, which enforced trees to a slight water deficit pre and post-harvest, resulted in statistically lower soil matric potential

Table 4

Mean value of stomatal conductance (gs), net photosynthesis (Pn) and intrinsic water use efficiency (IWUE) to each irrigation period pre-harvest (Pre), floral differentiation (Floral Diff) and post-harvest (Post) of the experimental period 2015–2018 to 'Prime Giant' sweet cherry trees exposed to four different irrigation treatments, control (CTL), sustained deficit irrigation (SDI), regulated deficit irrigation (RDI) and a treatment based on normal farming practices (FRM).

		gs (mmol m^{-2} s^{-1})					Pn (μmol m^{-2} s^{-1})					IWUE (μmol mol^{-1})				
		CTL	SDI	RDI	FRM	ANOVA	CTL	SDI	RDI	FRM	ANOVA	CTL	SDI	RDI	FRM	ANOVA
Pre		175.6	188.9	192.8	179.5	n.s.	10.0	10.9	10.0	10.3	n.s.	57.1	57.7	51.7	57.2	n.s.
Floral Diff	2015	337.4	331.0	261.3	309.3	n.s.	17.3	18.7	15.7	17.1	n.s.	51.2	56.6	56.9	55.3	n.s.
Post		211.0 a	175.7 b	119.7 c	154.6 bc	⁎	16.1 a	14.1 ab	11.8 b	11.7 b	⁎	76.2 b	80.5 b	98.5 a	75.5 b	⁎
Pre		182.0	167.3	175.8	191.4	n.s.	14.5	14.8	15.3	15.0	n.s.	79.4	88.7	86.8	78.2	n.s.
Floral Diff	2016	274.0	229.0	342.5	283.8	n.s.	17.5	17.3	20.8	18.1	n.s.	63.8	75.5	60.7	63.8	n.s.
Post		192.2 a	139.3 ab	101.1 b	79.4 b	⁎	15.6 a	11.5 bc	10.9 bc	8.8 c	⁎	81.2 b	82.7 b	108.0 a	110.5 a	⁎
Pre		178.8	173.1	184.3	182.5	n.s.	11.6	12.9	14.5	12.6	n.s.	68.4	74.3	68.5	69.1	n.s.
Floral Diff	2017	264.8 a	248.2 a	245.6 a	109.2 b	⁎	19.4	17.6	17.5	13.0	n.s.	73.3 b	70.8 b	71.2 b	118.7 a	⁎⁎
Post		185.7 a	149.0 ab	109.7 bc	84.5 c	⁎	16.0 a	14.2 b	12.1 bc	9.3 c	⁎	86.3 b	95.6 b	109.9 a	109.9 a	⁎⁎
Pre	2018	191.1	180.7	184.5	194.7	n.s.	14.6	15.1	12.7	15.0	n.s.	76.4	83.8	69.1	77.0	n.s.

Each value is the mean of the 4 replicates. Mean values within the same period (row) followed by a different letter denote significant differences among treatments according to Duncan multiple range test ($P < 0.05$). In the ANOVA column, ⁎, ⁎⁎ refer to significant effect at $P = 0.05$ or 0.01, respectively and n.s. to not significant.

and soil water content than all the other irrigation treatments during the pre-harvest period in three of the four years for the Ψm (Table 2), but only in the last two years for θv (Table 3).

Consequently, these differences in water availability affected the plant water status. Ψ_{stem} was a sensitive indicator for identifying tree water status according to the intensity of the water deficit applied. Ψ_{stem} identified significant differences not only after harvest between RDI and CTL, when RDI provides only 55% of the water requirements, but also between SDI and CTL during pre-harvest, when a mild deficit is applied in SDI (Fig. 1).

gs has been reported to be highly dependent on Ψ_{stem} and meteorological parameters in sweet cherry trees (Blanco et al., 2018). Thus, maximum gs and Pn annual values for all treatments coincided with pre-harvest and floral differentiation when evaporative demand rise and vegetative and reproductive sinks compete for carbohydrates. The pre-harvest period of 'Prime Giant' sweet cherry is short, lasts approximately 60 d (López-Ortega et al., 2017). Thus, during the last days of pre-harvest and floral differentiation, fruit growth, flower-bud differentiation, shoot extension and leaf growth coincide so there is competition for assimilates among the different processes (Yoon and Richter, 1990), making trees highly susceptible to water deficit during this time. An excessive water deficit in pre-harvest and floral differentiation would lead to stomatal closure, Pn decreases and consequently lower fruit and vegetative growth. The slight deficit irrigation applied in SDI trees during pre-harvest did not significantly decrease yield, but induced lower vegetative growth, especially in parameters such as current season shoot growth (Table 5). During post-harvest, when deficit irrigation was applied, RDI trees resulted in significantly lower gs and Pn than CTL trees every year of the study (Table 4), which suggests that in order to avoid excessive water losses sweet cherry trees regulate stomata closure in response to water stress. Pn showed significant differences between RDI and CTL only when deficit irrigation was applied in RDI. Pronounced and severe reductions of gs affected Pn, so slight water deficit did not cause Pn reductions. These results are consistent with those of Antunez-Barria (2006) and Marsal et al. (2009), who describe a drop in Ψ_{stem} caused by deficit irrigation and reduced Pn in 'Bing' and 'New Star' trees. According to the results obtained, the values of gs (close to 100 mmol m^2 s^{-1}) and Pn (close to 10 μmol m^2 s^{-1}), during post-harvest had no negative effects on the following year's yield and fruit quality (Fig. 3), although vegetative growth was affected (Table 5).

MDS increased as did the evaporative demand. During pre-harvest, MDS of CTL, RDI and FRM trees increased more than four times, among them FRM trees had the lowest MDS due to the high amounts of water available, especially in 2015 and 2016. MDS of SDI trees had a significantly higher increased of MDS during pre-harvest compared with the trees of the other irrigation treatments. When deficit irrigation was applied in the post-harvest period, the MDS of RDI trees rapidly increased, as can be seen in the SI_{MDS} mean values recorded. SI_{MDS} has been successfully used in irrigation management in fruit trees (Puerto et al., 2013). Absolute values of tree water status indicators are highly dependent of environmental conditions, canopy architecture, soil variability, etc. Consequently, replication of irrigation strategies is limited. In order to ease the replication of the irrigation strategies followed, the SI_{MDS} mean values obtained according to tree phenology are provided. Thus, the trees whose SI_{MDS} during pre-harvest was above 1.3 had lower current season shoot growth and tended to smaller fruit (Fig. 4, Table 5). On the other hand, during post-harvest, the trees with SI_{MDS} values of around 1.6 had a lower canopy volume and produced less pruning wood, but this did not penalize the following year's yield. It was also observed that FRM trees that were over-irrigated during pre-harvest ($SI_{MDS} = 0.9$) did not give a higher fruit yield but increased the pruning wood, which increased crop management costs.

The effects of water deficit on tree's vegetative growth could also be identified in the BGR. Similarly to MDS, BGR presented different values according to the irrigation regime (Fig. 2). However, as evaporative

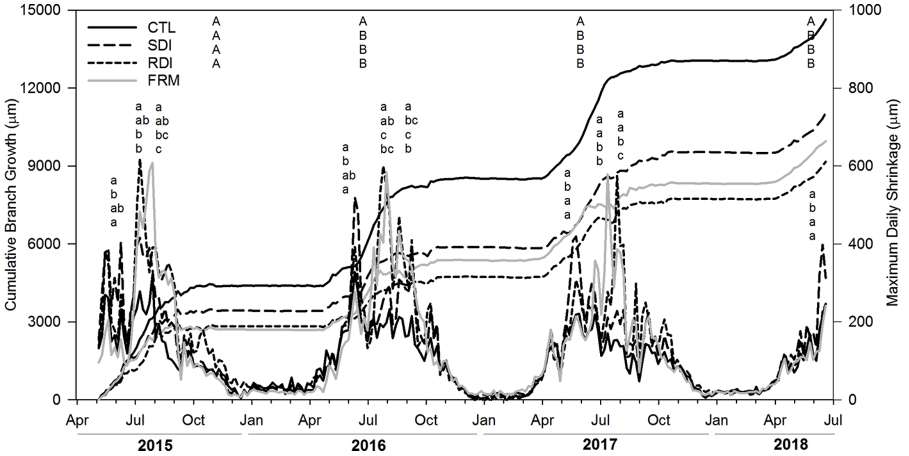

Fig. 2. Evolution of the branch maximum daily shrinkage (MDS) and cumulative branch growth during the experimental period 2015–2018 of 'Prime Giant' sweet cherry trees exposed to four different irrigation treatments, control (CTL, solid black line), sustain deficit irrigation (SDI, long dashed line), regulated deficit irrigation (RDI, short dashed line) and a treatment based on normal farming practices (FRM, grey line).

Represented values are the mean of 6 measurements during a period of 5 days. Different lower case letters denote significant differences among treatments to MDS, 10 days before harvest and 10 and 20 days after floral differentiation, and different upper case letters denote significant differences among treatments to cumulative branch growth at harvest, according to Duncan multiple range test ($P < 0.05$). Both upper and lower case letters are (in order) from top to bottom, CTL the top letter, SDI the second top letter, RDI the third top letter and FRM the bottom letter.

demand increased in late pre-harvest, differences between the trees of the different irrigation treatment arose. Theses differences were more evident in 2016, a high cropping year. Thus, in the days immediately before the 2016 harvest, SDI trees had BGR 27% lower than CTL. Consequently, the highest BGR values were recorded each season in CTL from June to July (65–75 $\mu m\, d^{-1}$), which is in line with the higher increase of TCSA measured in those trees (Table 5). Once the deficit irrigation was applied during post-harvest, BGR of RDI trees decreased sharply, which, at the end of the last season as a consequence of deficit irrigation, trees of RDI resulted in an accumulated BGR that was 1700 and 5500 µm lower than the trees of SDI and CTL, respectively (Fig. 2). That is an important effect of deficit post-harvest irrigation on tree's vegetative growth. Other authors have also reported that an irrigation deficit inhibits vegetative growth (Chalmers et al., 1981; Mitchell and Chalmers, 1982).

This cumulative effect of deficit irrigation on BGR was also noted in other vegetative growth indicators. Dehghanisanji et al. (2007) reported the strong effect of deficit irrigation on sweet cherry canopy volume. In our experiment, in the second year RDI trees had already reduced tree canopy volume and PFR intercepted by 7% and 17%, respectively, compared with CTL trees; however, the differences were not statistically significant until the third year of the experiment. There were no significant different in TCSA among treatments any year of the study. However, at the end of the experiment, irrigation effect on the TCSA of the trees was greater, TCSA of CTL trees during the experiment had grown by 79 cm^2 (23, 38 and 24% more than SDI, RDI and FRM trees, respectively, Table 5). TCSA increases were proportional to the water applied to each irrigation treatment. Neilsen et al. (2014) described irrigation management (amount and frequency) as one of the strongest factors in TCSA growth in sweet cherry trees. Annual shoot growth was sensitive to water restrictions when other vegetative growth indicators were not. SDI and RDI trees in 2017 produced half of the annual shoot growth of CTL trees. In sweet cherry, current season shoots grow throughout pre-harvest; however, sometimes it can last longer (first post-harvest days) although 80% of the shoot growth takes place while the fruit is growing (Ayala and Lang, 2015; Rivera et al., 2016); thus, SDI trees, which were the only trees that did not completely satisfy the water requirements during pre-harvest, produced the lowest annual shoot growth in 2017 (Table 5). These results match those reported by Livellara et al. (2011) and Podesta et al. (2010) in 'Brooks and' 'Bing' sweet cherry trees, who described current season shoot long as an early indicator of water reductions in pre-harvest. All these differences in vegetative growth were consistent with the amount of wood pruned, which gradually increased in CTL trees, while significantly lower results were obtained for SDI, RDI and FRM trees for the last 2 years. Comparing the deficit treatments, SDI trees resulted in the lowest shoot growth, while RDI trees led to the smallest canopy volume, pruning wood, TCSA and lower shoot growth than control trees. Thus, RDI treatment had a greater impact on tree vegetative growth than SDI treatment, which agreed with the results mentioned above for soil and plant water deficit indicators.

The way in which deficit irrigation was applied in RDI and SDI, avoiding Ψ_{stem} values below -1.6 MPa during post-harvest deficit irrigation, might be reason why fruit yields were not significantly penalized in the subsequent seasons. Marsal et al. (2009) proposed -1.5 MPa as the Ψ_{stem} threshold value in post-harvest deficit irrigation so as not to affect the following season's yield. However, in 2017 post-harvest, FRM trees produced a one-off Ψ_{stem} value below -1.8 MPa that did not cause a significantly lower yield, although FRM was the least productive treatment (Fig. 3A). Although there were no significant differences among irrigation treatments in total or partial yield, number of fruit per tree or unitary fruit mass at harvest, SDI trees, especially at the first harvest, led to higher number of fruits per tree but of lower unitary fruit mass than CTL fruit, particularly in 2017 and 2018. Fruits of SDI trees were almost 1 g smaller than those from CTL trees (Fig. 3C). Lower unitary mass in sweet cherry fruit is closely related to lower crop profitability; and, although there were no significant differences in fruit unitary mass among treatments, there was a clear trend for SDI trees to produce fruit of the smallest categories, equatorial diameter < 28 mm (Fig. 4). These results concerning SDI fruit unitary mass can be related to the significantly lower Ψ_{steam} values during pre-harvest, which suggests a closer relationship between lower fruit unitary mass and a decrease in plant water status during pre-harvest rather than during post-harvest (Fig. 1). The slight water deficit applied during early pre-harvest did not induce higher cherry run-off; on the contrary it could have induced a slightly higher number of fruit per tree which added to the water deficit applied during late pre-harvest (final phase of fruit development), affected fruit size. Consequently, the combined effect of higher number of fruit per tree and water deficit during fruit cell enlargement in SDI trees tended to produce fruit of smaller size (Fig. 3). Similarly, SDI fruit led to higher SSC than CTL fruit but without significant differences. Higher SSC values are typically associated with RDI treatments. In tart cherry, Papenfuss and Black (2010) also reported higher SSC values as a result of deficit treatments, but only described

Table 5

Influence of four irrigation treatments, control (CTL), sustained deficit irrigation (SDI), regulated deficit irrigation (RDI) and a treatment based on normal farming practices (FRM) on the vegetative growth of 'Prime Giant' sweet cherry trees over the seasons (2015–2018).

	Pruning wood (kg tree^{-1})						Canopy volume (m^3)				Phoyosynthetic Photon Flux Rate (μmol m^{-2} s^{-1})				Trunk Cross Section Area (cm^2)				Shoot growth (m)			
	2015		2016		2017		2015	2016	2017		2015	2016	2017		2015	2016	2017	2018	2016		2017	
CTL	4.54	b	7.69	a	9.32	a	9.62	10.76	11.20	a	780	805	875	a	214	241	260	293	0.30	a	0.44	a
SDI	3.45	b	5.42	bc	5.33	bc	10.14	10.77	9.80	ab	752	637	692	ab	236	260	278	302	0.21	b	0.22	b
RDI	3.56	b	5.05	c	4.29	c	9.98	10.05	9.29	b	726	683	544	b	216	230	242	263	0.20	b	0.25	b
FRM	6.59	a	6.47	b	5.89	b	10.45	11.43	10.73	ab					229	255	267	290	0.27	ab	0.34	ab
ANOVA	⁎		⁎⁎		⁎⁎⁎		n.s.	n.s.	⁎		n.s.	n.s.	⁎		n.s.	n.s.	n.s.	n.s.	⁎		⁎	

Each value is the mean of the 4 replicates. Different letters on the same parameter (column) denote significant differences among treatments, according to Duncan multiple range test ($P < 0.05$). In the ANOVA row, ⁎, ⁎⁎, ⁎⁎⁎ refer to significant effect at $P = 0.05$, 0.01 or 0.001, respectively and n.s. to not significant.

significant differences in the sustained deficit irrigation treatment which satisfied 30% of the ETc.

These effects of deficit irrigation on fruit mass could also be enhanced not only by water stress, but also by the different crop loads registered among seasons. Yield differences among years affected fruit unitary mass, and a high crop load itself was a factor affecting fruit mass at harvest (Fig. 3C). Thus, mean unitary fruit mass in 2016, the year with the largest crop load, was almost 3 g lower than in 2015 and 2017. However, in all harvests SDI trees lead to produce lower mean unitary fruit mass than CTL trees. The linear relationship between crop load and unitary mass obtained using the data for all years of the study suggests that the yield should not exceed 24–25 t ha^{-1} if a unitary fruit mass of 10 g is to be achieved. Since sweet cherry price is positively correlated with fruit size, yields higher than 25 t ha^{-1} will lower the price and consequently the profits of growers.

There was no clear influence of irrigation management in our growing conditions on the occurrence of double fruits. In crops such as peach or nectarine, post-harvest water deficit during summer has been demonstrated to increase the proportion of double fruits (Johnson et al., 1992; Naor et al., 2005). However, no such effect was evident in our experiment. Even in the 2017 post-harvest period, when soil water deficit indicators recorded minimum values (Table 2 and 3) and Ψ_{stem} fell below -1.8 MPa in FRM (Fig. 1), neither RDI nor FRM led to significantly more double fruits than CTL. However, in 2018 SDI treatment resulted in a higher proportion of double fruits (9%) than the other treatments. Beppu et al. (2001) and Roversi et al. (2008) reported that high temperatures during flower differentiation, especially during sepal to petal differentiation, might cause greater incidence than water deficit.

In both 2017 and 2018, cracked fruit were recorded at harvest. It is well known that rain-induced cracking is the major cause of crop loss in sweet cherry (Correia et al., 2018) and that sensitivity to fruit cracking is highly dependent on the cultivar. According to our results, 'Prime Giant' can be considered sensitive to fruit cracking (Table 6). In 2018, several rain episodes prior to harvest caused a loss of total yield with differences observed among treatments. Fruit of SDI and RDI resulted in a lower incidence of rain-induced cracking. This behaviour might be related with fruit lower water content and thicker skin in fruit of deficit irrigation treatments, as thicker fruit cuticle has been related as an effect of deficit irrigation on fruit (Pérez-Pastor et al., 2007). These results were consistent with the cracking index calculated in the laboratory, where RDI and SDI fruit were seen to be less likely to crack (Table 6). The result of a lower cracking index is a longer shelf-life, since fruit prone to cracking are also prone to developing diseases during storage (Zoffoli et al., 2017).

Of the four irrigation strategies assayed, RDI led to the greatest WP every year of the study (Table 7). SDI treatment also exhibited significant differences with CTL. A higher WP in deficit irrigation treatments has been reported in other crops such as peach, citrus and almond (Ghrab et al., 2013; Gonzalez-Altozano and Castel, 1999; Puerto et al., 2013).

RDI trees tended to higher FE than all the other trees, however, there were no significant differences among irrigation treatments any year of the study. Regarding YE, there were significant differences among treatments in 2018. RDI trees were the most productive trees per trunk section, whereas FRM and SDI trees did not result in statistical higher YE than CTL trees (Table 7). Significant differences in FTI and YE were due to the effect of the irrigation treatment on trunk growth more than on yield. Even though there were no differences in yield among treatments, the TCSA in CTL increased during the experiment by 10% more than in RDI (Table 5). The YE results obtained were similar to those reported by Nieto et al. (2017) but lower than those of Larsen et al. (1987) for adult trees. These lower results could be due to the rootstock used (SL64). SL64 has been reported by López-Ortega et al. (2016) and Aglar and Yildiz (2014) as a rootstock that produces low YE in sweet cherry cultivars such as 'New Star' and '0900 Ziraat'.

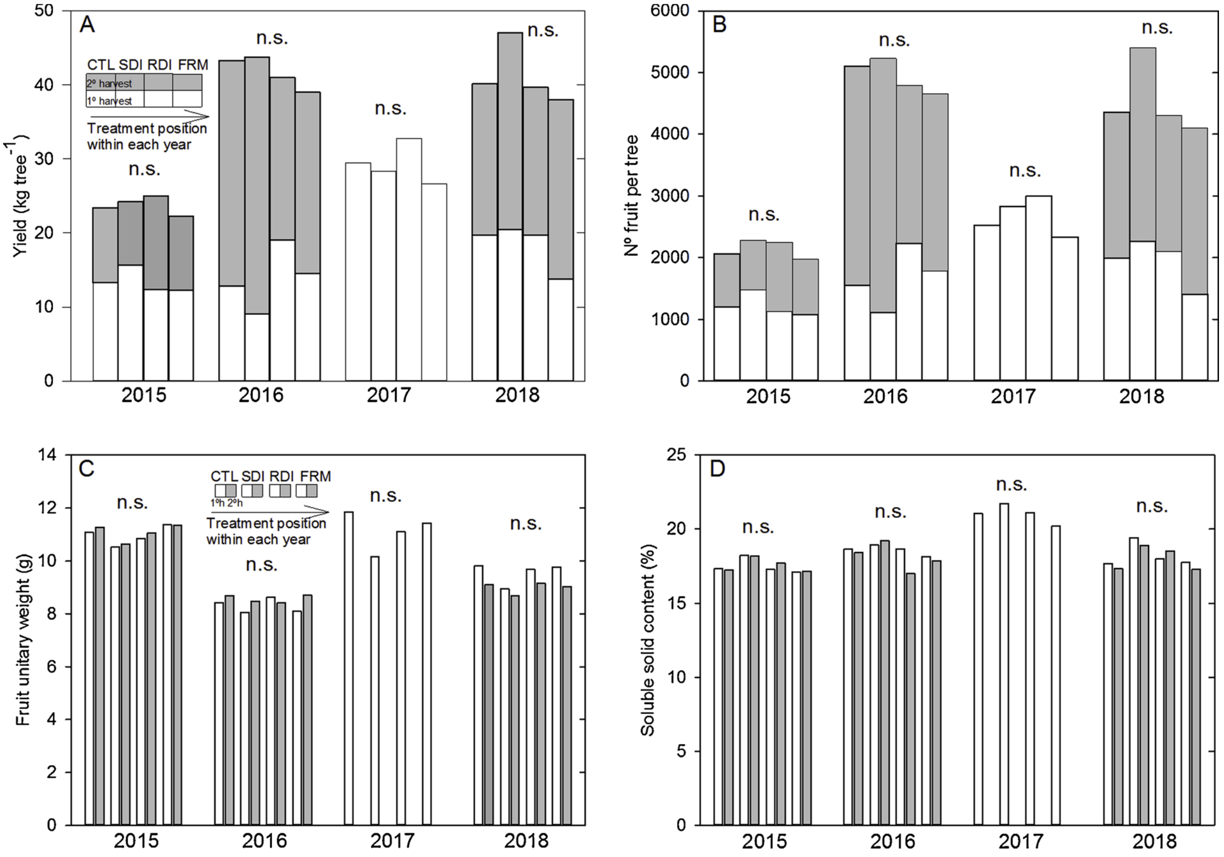

Fig. 3. Influence of four irrigation treatments, control (CTL), sustained deficit irrigation (SDI), regulated deficit irrigation (RDI) and a treatment based on normal farming practices (FRM) on 'Prime Giant' sweet cherry yield (A), number of fruits per tree (B), fruit unitary weight (C), and soluble solid content (D) over the harvest (2015–2018).

Each value is the mean of the 4 replicates. n.s. denotes no significant differences among treatments neither total nor partial harvests within each year according to ANOVA ($P < 0.05$). Within each year treatments are, in order, from left to right CTL, SDI, RDI and FRM. First and second harvests are white and grey colored, respectively.

5. Conclusion

A water saving of 39% with RDI did not penalize total fruit yield or quality, particularly fruit size. The regulated water deficit imposed during post-harvest in RDI trees decreased stomatal conductance and stem water potential, which resulted in lower vegetative growth than obtained in CTL trees. Similarly, SDI treatment, which saved 28% of the water applied compared with CTL treatment, provided similar yields and lower vegetative growth. However, SDI trees tended to produce smaller fruits, which would negatively affect grower's profits. Therefore, as long as there is water available during the pre-harvest period, even slight water deficits must be avoided. Fruit of both water deficit treatments led to similar SSC and lower cracking susceptibility than CTL and FRM fruit, which could be a key factor for storage and shelf-life. It was seen that the vegetative growth of sweet cherry trees exposed to post-harvest water deficit was more affected than reproductive growth.

Table 6
Percentage of double and cracked fruits and cracking index of 'Prime Giant' sweet cherry fruit from four different irrigation treatments, control (CTL), sustained deficit irrigation (SDI), regulated deficit irrigation (RDI) and a treatment based on normal farming practices (FRM).

	Double fruit (%)				Cracked fruit (%)					Cracking Index			
	2015	2016	2017	2018	2017	2018				2018			
						1st harvest		2nd harvest		1st harvest		2nd harvest	
CTL	11.6	2.3	2.4	5.5	1.5	22.9	a	23.9	a	57	a	66	a
SDI	14.9	1.6	1.5	9.2	0.6	9.3	b	9.7	bc	42	b	47	b
RDI	12.2	1.7	0.9	5.0	0.7	14.8	ab	8.1	c	47	b	49	b
FRM	14.6	2.0	1.3	6.2	1.3	20.9	a	18.0	ab	64	a	67	a
ANOVA	n.s.	n.s.	n.s.	n.s.	n.s.	⁎		⁎⁎		⁎		⁎	

Each value is the mean of the 4 replicates. In cracked fruit and cracking index, first and second harvest of 2018 were differentiated. Different letters on the same parameter and year (column) denote significant differences among treatments, according to Duncan multiple range test ($P < 0.05$). In the ANOVA row, ⁎, ⁎⁎ refer to significant effect at $P = 0.05$ or 0.01, respectively and n.s. to not significant.

Table 7

Irrigation water productivity (WP), fruit efficiency (FE), fruits per trunk increment (FTI) and yield efficiency (YE) over the seasons (2015–2018) to 'Prime Giant' sweet cherry trees exposed to four different irrigation treatments, control (CTL), sustained deficit irrigation (SDI), regulated deficit irrigation (RDI) and a treatment based on normal farming practices (FRM).

	WP (kg m^{-3})						FE (fruits cm^{-2} trunk)			FTI (fruits cm^{-2} trunk increment)					YE (kg cm^{-2})			
	2016		2017		2018		2016	2017	2018	2016		2017	2018		2016	2017	2018	
CTL	2.52	c	1.79	c	2.37	c	21.15	9.73	14.41	200.3	b	279.8	130.0	b	0.179	0.113	0.135	b
SDI	3.51	b	2.58	ab	3.80	b	20.51	10.17	17.94	226.1	b	334.0	315.1	a	0.170	0.103	0.157	ab
RDI	4.47	a	3.87	a	5.33	a	21.17	12.66	22.20	329.2	a	338.6	248.2	a	0.178	0.138	0.203	a
FRM	2.66	bc	2.09	bc	3.92	b	18.35	8.74	18.78	183.6	b	188.8	240.3	a	0.154	0.094	0.177	ab
ANOVA	⁎⁎		⁎⁎⁎		⁎⁎⁎		n.s.	n.s.	n.s.	⁎		n.s.	⁎⁎		n.s.	n.s.	⁎	

Each value is the mean of the 4 replicates. Different letters on the same parameter and year (column) denote significant differences among treatments, according to Duncan multiple range test ($P < 0.05$). In the ANOVA row, ⁎, ⁎⁎, ⁎⁎⁎ refer to significant effect at $P = 0.05$, 0.01 or 0.001, respectively and n.s. to not significant.

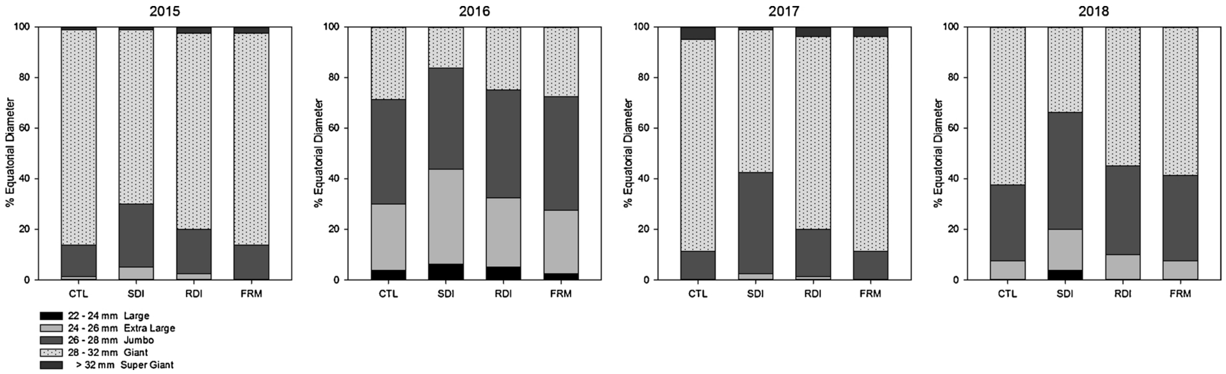

Fig. 4. Fruit size distribution at harvest (2015–2018) of 'Prime Giant' sweet cherry trees subjected to four irrigation treatments, control (CTL), sustained deficit irrigation (SDI), regulated deficit irrigation (RDI) and a treatment based on normal farming practices (FRM).
Each distribution is the mean of 20 fruit per replicate, and 4 replicates per treatment.

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References

Aglar, E., Yildiz, K., 2014. Influence of Rootstocks (Gisela 5, Gisela 6, MaxMa, SL 64) on performance of 0900 Ziraat Sweet Cherry. J. Basic Appl. Sci. 10, 60–66.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. FAO Irrigation and Drainage Paper 56. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO, Rome.

Antunez-Barria, A.J., 2006. The Impact of Deficit Irrigation Strategies on Sweet Cherry (Prunus Avium L) Physiology and Spectral Reflectance. PhD Diss.. Washington State Univ. UMI Microform 3252310.

Ayala, M., Lang, G., 2015. 13C Photoassimilate partitioning in sweet cherry (Prunus avium) during early spring. Cienc. Investig. Agrar. 42, 191–203.

Beppu, K., Ikeda, T., Kataoka, I., 2001. Effect of high temperature exposure time during flower bud formation on the occurrence of double pistils in 'Satohnishiki' sweet cherry. Sci. Hortic. 87, 77–84.

Blanco, V., Domingo, R., Pérez-Pastor, A., Blaya-Ros, P.J., Torres-Sánchez, R., 2018. Soil and plant water indicators for deficit irrigation management of field-grown sweet cherry trees. Agric. Water Manage. 208, 83–94.

Centritto, M., 2005. Photosynthetic limitations and carbon partitioning in cherry in response to water deficit and elevated [CO2]. Agric. Ecosyst. Environ. 106 (2), 233–242.

Chalmers, D.J., Mitchell, P.D., van Heek, L., 1981. Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. J. Am. Soc. Hortic. Sci. 106 (3), 307–312.

Christensen, J.V., 1972. Cracking in cherries. III. Determination of cracking susceptibility. Acta Agric. Scand. 22, 128–136.

Correia, S., Schouten, R., Silva, A.P., Gonçalves, B., 2018. Sweet cherry fruit cracking mechanisms and prevention strategies: a review. Sci. Hortic. 240, 369–377.

de la Rosa, J.M., Domingo, R., Gómez-Montiel, J., Perez-Pastor, A., 2015. Implementing deficit irrigation scheduling through plant water stress indicators in early nectarine trees. Agric. Water Manage. 152, 207–216.

Dehghanisanij, H., Naseri, A., Anyoji, H., Eneji, A.E., 2007. Effects of deficit irrigation and fertilizer use on vegetative growth of drip irrigated cherry trees. J. Plant Nutr. 30, 411–425.

FAO, 2002. The State of Food and Agriculture. Agriculture and Global Public Goods Ten Years After the Earth Summit. Rome. ISBN 92-5-104762-6. .

FAOSTAT - Food and Agriculture Organization of the United Nations Statistics Division, 2015 available on. http://www.fao.org/faostat/en/#data/QC/visualize (Accessed: October 2018).

Fereres, E., Evans, R.G., 2006. Irrigation of fruit trees and vines: an introduction. Irrigation Sci. 24, 55–57.

Fereres, E., Martinich, D.A., Aldrich, T.M., Castel, J.R., Holzapfel, E., Schulbach, H., 1982. Drip irrigation saves money in young almond orchards. Calif. Agric. (Berkeley) 36, 12–13.

Ghrab, M., Zitouna, R., Ben-Mimoun, M., Masmoudi, M.M., Ben-Mechlia, N., 2013. Yield and water productivity of peach trees under continuous deficit irrigation and high evaporative demand. Biol. Agric. Hortic. 29 (1), 29–37.

Girona, J., Gelly, M., Mata, M., Arbones, A., Rufat, J., Marsal, J., 2005. Peach tree response to single and combined deficit irrigation regimes in deep soils. Agric. Water Manage. 72, 97–108.

Goldhamer, D.A., Fereres, E., 2001. Irrigation scheduling protocols using continuously recorded trunk diameter measurements. Irrig. Sci. 20, 115–125.

Gonzalez-Altozano, P., Castel, J.R., 1999. Regulated deficit irrigation in' Clementina de Nules' citrus trees. I. Yield and fruit quality effects. J. Hortic. Sci. Biotechnol. 74 (6), 706–713.

Hutchison, D.J., 1978. Influence of rootstock on the performance of "Valencia" sweet orange. Proc. Int. Soc. Citricult. 2, 523–525.

Intrigliolo, D.S., Castel, J.R., 2006. Performance of various water stress indicators for prediction of fruit size response to deficit irrigation in plum. Agric. Water Manage. 83, 173–180.

Johnson, R.S., Handley, D.F., DeJong, T.M., 1992. Longterm response of early maturing peach trees to postharvest water deficits. J. Am. Soc. Hortic. Sci. 117, 881–886.

Larsen, F.E., Higgins, S.S., Fritts, R., 1987. Scion/interstock/rootstock effect on sweet cherry yield, tree size and yield efficiency. Sci. Hortic. 33, 237–247.

Livellara, N., Saavedra, F., Salgado, E., 2011. Plant based indicators for irrigation scheduling in young cherry trees. Agric. Water Manage. 98, 684–690.

López-Ortega, G., García-Montiel, F., Bayo-Canha, A., Frutos-Ruiz, C., Frutos-Tomás, D., 2016. Rootstock effects on the growth, yield and fruit quality of sweet cherry cv. 'Newstar' in the growing conditions of the Region of Murcia. Sci. Hortic. 198, 326–335.

López-Ortega, G., García-Montiel, F., Bayo-Canha, A., Frutos-Ruíz, C., Frutos-Tomás, D., 2017. Influence of climate change on sweet cherry phenology in Murcia. Spain. Acta Hortic. 1162, 51–56.

Marsal, J., 2012. FAO Irrigation and Drainage Paper 66. Crop Yield Response Water. Sweet Cherry. FAO, Rome, pp. 449–457.

Marsal, J., López, G., Arbones, A., Mata, M., Vallverdu, X., Girona, J., 2009. Influence of postharvest deficit irrigation and pre-harvest fruit thinning on sweet cherry (cv. New Star) fruit firmness and quality. J. Hortic. Sci. Biotechnol. 84 (3), 273–278.

Marsal, J., López, G., del Campo, J., Mata, M., Arbones, A., Girona, J., 2010. Postharvest regulated deficit irrigation in Summit sweet cherry: fruit yield and quality in the following season. Irrig. Sci. 28, 181–189.

McCutchan, H., Shackel, K.A., 1992. Stem-water potential as a sensitive indicator ofwater stress in prune trees (Prunus domestica L. cv French). J. Am. Soc. Hortic. Sci. 117, 607–611.

Mitchell, P.D., Chalmers, D.J., 1982. The effect of reduced water supply on peach tree growth and yields. J. Am. Soc. Hortic. Sci. 107, 853–856.

Morais, R., Fernandes, M.A., Matos, S.G., Serodio, C., Ferreira, P.J.S.G., Reis, M.J.C.S., 2008. A ZigBee multi-powered wireless acquisition device for remote sensing applications in precision viticulture. Comput. Electron. Agric. 62, 94–106.

Naor, A., Stern, R., Peres, M., Greenblat, Y., Gal, Y., Moshe, A., Flaishman, M., 2005. Timing and severity of postharvest water stress affect following-year productivity and fruit quality of field-grown 'Snow Queen' nectarine. J. Am. Soc. Hortic. Sci. 130, 806–812.

Neilsen, G.H., Neilsen, D., Kappel, F., Forge, T., 2014. Interaction of irrigation and soil management on sweet cherry productivity and fruit quality at different crop loads that simulate those occurring by environmental extremes. HortScience. 49 (2), 215–220.

Nieto, E., Prieto, M.H., Fortes, R., Gonzalez, V., Campillo, C., 2017. Response of a long-lived cherry cultivar to contrasting irrigation strategies in the Jerte Valley, Extremadura, Spain. Acta Hortic. 1161, 197–204.

Papenfuss, K.A., Black, B.L., 2010. Regulated deficit irrigation of' Montmorency' Tart cherry. Hortscience. 45 (10), 1437–1440.

Pérez-Pastor, A., Ruiz-Sánchez, M.C., Martínez, J.A., Nortes, P.A., Artés, F., Domingo, R., 2007. Effect of deficit irrigation on apricot fruit quality at harvest and during storage. J. Sci. Food Agric. 87, 2409–2415.

Pérez-Pastor, A., Domingo, R., Torrecillas, A., Ruiz-Sánchez, M.C., 2009. Response of apricot trees to deficit irrigation strategies. Irrig. Sci. 27, 231–242.

Podesta, L., Sanchez, E.E., Vallone, R., Morábito, J., 2010. Effect of water deficit irrigation on vegetative growth of young cheery trees (Prunus avium L.). Rev. FCA UNCuyo. 42 (1), 73–91.

Puerto, P., Domingo, R., Torres, R., Pérez-Pastor, A., García-Riquelme, M., 2013. Remote management of deficit irrigation in almond trees based on maximum daily trunk shrinkage. Water relations and yield. Agric. Water Manage. 126, 33–45.

Rivera, R., Bañados, P., Ayala, M., 2016. Distribution of 15N applied to the soil in the "Bing"/"Gisela®6"sweet cherry (Prunus avium L.) combination. Sci. Hortic. 210, 242–249.

Roversi, A., Monteforte, A., Panelli, D., Folini, L., 2008. Observations on the occurrence of sweet cherry double-fruits in Italy and Slovenia. Acta Hort. 795, 849–854.

Saccon, P., 2018. Water for agriculture, irrigation management. Agric., Ecosyst. Environ., Appl. Soil Ecol. 123, 793–796.

SIAR. Servicio Integral de Asesoramiento al Regante. http://crea.uclm.es/siar/datmeteo/.

Torrecillas, A., Domingo, R., Galego, R., Ruiz-Sánchez, M.C., 2000. Apricot tree response to withholding irrigation at different phenological periods. Sci. Hortic. 85, 201–215.

Tricase, C., Rana, R., Andriano, A.M., Ingrao, C., 2017. An input flow analysis for improved environmental sustainability and management of cherry orchards: a case study in the Apulia region. J. Clean. Prod. 156, 766–774.

UNESCO, 2001. Valuing Water. World Water Assessment Programme. United Nations. United Nations Education Scientific and Cultural Organization, Paris).

Yoon, T.M., Richter, H., 1990. Seasonal changes in stomatal responses of sweet cherry and plum to water status in detached leaves. Physiol. Plant. 80, 520–526.

Zoffoli, J.P., Toivonen, P., Yan, Wang, 2017. Postharvest biology and handling for fresh markets. Chapter 19 In: Quero-García, J., Iezzoni, A., Pulawska, J., Lang, G. (Eds.), Cherries: Botany, Production and Uses. CABI, Oxfordshire, Wallingford, pp. 460–484.