Responses of sweet cherry trees to regulated deficit irrigation applied before and after harvesting

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Abstract

The current study was conducted over four years between 2016 and 2019 to determine the effects of regulated deficit irrigation (RDI) before and after harvesting of sweet cherry on yield, physiological, vegetative and fruit quality parameters. The current study used the 0900 Ziraat sweet cherry cultivar grafted onto Gisela 6 rootstock. There were six different treatments: I_C, (Control) where soil moisture was kept at field capacity for each irrigation, I_{25}, with 25% deficit irrigation of I_C after harvesting, I_{50}, with 50% deficit irrigation of I_C after harvesting, I_{25BH}, with no-deficit irrigation 30 days after full bloom and 25% deficit irrigation after this period, I_{50BH}, with no-deficit irrigation 30 days after full bloom and 50% deficit irrigation after this period, and I_{FRM}, with farmer's treatment of excessive irrigation (150% of ET) from colouring of fruit till harvest and 50% deficit irrigation after harvesting. When compared to I_C, water saving ranged from 20.2–45.6%. The fruit yield obtained under I_{25} was increased by 21.8% in the last year of the current study than the yield obtained under I_C treatment. Trunk and shoot growth increased for all treatments. Leaf water potential (Ψ_{md}) and stomata conductance (g_{sw}) were affected by RDI. I_{FRM} and I_{25} had a positive effect on fruit size, the same as I_C. Water deficit (I_{BH50}) applied before harvesting increased fruit flesh firmness. I_{25} treatment (25% water deficit after harvesting) can be applied by sweet cherry growers because it leads to high yield, better fruit quality and water saving.

Introduction

All over the world, agriculture, industry, and other sectors share fresh water. Agriculture production takes the most, with a 70% usage rate generally and it exerts a constant pressure on freshwater resources (FAO, 2017). Therefore, water saving practices need to be applied in agricultural production. At the same time, irrigation practices which save water help to protect the environment. Farmers must prepare to face new challenges imposed by ongoing global warming, which is leading to warmer temperatures, constant droughts and the overuse of fresh ground water.

Agricultural areas are often located in arid and semi-arid regions where fresh water is the most limited resource. Many climate change models predict more arid climate conditions for the future (Collins *et al.*, 2013). The Mediterranean region in particular has relatively lower rainfall with an irregular distribution during the year and most precipitation in winter. The Mediterranean basin has the highest evapotranspiration in the summer months, and this leads to severe water deficit conditions. Therefore, irrigation becomes more critical in these months (Lo Bianco *et al.*, 2012).

Deficit irrigation (DI) strategies are recommended for irrigated fruit trees to save irrigation water with an acceptable reduction in yield. In fruit production, regulated deficit irrigation (RDI) is a technique that was developed to save water and minimize inputs in irrigation in areas where freshwater resources are limited (Talluto *et al.*, 2008; Ruiz-Sánchez *et al.*, 2010). Ruiz-Sánchez *et al.* (2010) claimed that RDI is a technique providing water saving of up to 40% without any negative effect on yield. Furthermore, RDI prevents excessive vegetative growth in many fruit crops in certain conditions and has positive effects on fruit quality parameters like soluble solid content, fruit firmness and skin colour (Blanco, 2019). However, these applications need to be formulated (Ebel *et al.*, 1995), and this approach requires clear information about: (1) what are responses of fruit trees to water stress at different growing periods? and (2) Which growing periods of fruit trees are less sensitive to water stress? Determining the application period of deficit irrigation is necessary for fruit trees (Fereres and Goldhamer, 1990).

Studies have shown that RDI applications saved around of 40% irrigation water and had no negative effects on yield, fruit size and fruit quality on peach, nectarine and apricot trees (Torrecillas *et al.*, 2000; Girona *et al.*, 2005; Pérez-Pastor *et al.*, 2009; de la Rosa *et al.*, 2015; Blanco *et al.*, 2019). When water stress is applied excessive or at the wrong moment, fruit

size and yield are affected in fruit trees. There is limited information on the response of sweet cherry to water deficit strategies and drought stress and there is also very little information on fruit quality (Dehghanisanij et al., 2007; Marsal et al., 2009, 2010; Livellara et al., 2011; Nieto et al., 2017), vegetative growth and long period yield in the Mediterranean Basin (Blanco et al., 2019).

Sweet cherry (Prunus avium L.) is more sensitive to water stress than other cherry species (sour and tart cherries) before and after harvesting periods (Chockchaisawasdee et al., 2016). Sweet cherry trees are sensitive to water stress especially before harvest. However, there is very little information on the effects of water deficit applications on the vegetative and generative response of sweet cherry in the Mediterranean Basin, where summer periods are dry (Centritto, 2005). Because sweet cherry is harvested at an early stage of the growing season, irrigation applied before and after harvest becomes important for yield, fruit quality and irrigation water saving in the growing year and in following years.

In 2019, global sweet cherry production was 2 638 179 tons, and Turkey ranked in first place with 664 224 tons in 2019 (FAO, 2021). Turkey's share in the EU market is over 90%. One of the main problems in sweet cherry growing in Turkey is to decrease the amount of irrigation water, especially after harvest. The second problem is farmers' practice of applying excessive irrigation water about three weeks before harvest to improve the fruit size according to farmer practice (Yıldız et al., 2021). Farmers usually apply 50% more water during this period than the sweet cherry trees require. Harvest time for sweet cherry is in the middle of the growing period. This is why after harvesting, growers can neglect full irrigation or irrigation that sweet cherry needs. These practices negatively affect not only the yield obtained in the same year, but they also have negative effect on the yield and fruit quality of the next year (Doorenbos et al., 1986). Therefore, to tackle this problem, a study was needed to determine the effects of RDI on sweet cherry fruits and trees.

The cherry cultivar 0900 Ziraat dominates sweet cherry production and trade in Turkey (Mert and Soylu, 2007). Additionally, it is the cultivar most preferred by producers. The current study was the first to be performed on the effects of RDIs on sweet cherry before and after harvesting on sweet cherry yield, fruit quality and tree development in the areas where the 0900 Ziraat sweet cherry cultivar is grown. The current study covered four years, and with this feature, it differs from other studies. A study conducted over a long period with fruit trees can give more reliable results. The aim of the current study was (1) to determine the effects of different irrigation strategies applied before and after harvesting on the yield, tree physiology, vegetative development and fruit quality of the 0900 Ziraat sweet cherry cultivar, (2) to develop deficit irrigation scheduling in order to save water against water deficit in growing seasons because of the decreasing availability of water resources, and (3) to determine

the most suitable treatment for sweet cherry growers under RDIs conditions.

Materials and methods

The current study area and plant material

The current study was conducted at Eğirdir Fruit Research Institute (920 m altitude, 37° 49′18.24′′N, 30° 52′22.90′′E, Eğirdir, Isparta-Turkey) for four years (2016–2019). The current study area has a transition climate between the Mediterranean and Central Anatolia. Mediterranean summers are hot and dry, and winters are mild and rainy. The climate of Central Anatolia is one of hot summers and cold winters. The region also experiences significant temperature fluctuations between day and night. Maximum temperatures can reach 40°C in the summer months and drop below freezing in the winter. In the current study, the 0900 Ziraat sweet cherry cultivar grafted onto Gisela 6 rootstock was used. The sweet cherry trees were planted in 2010 at a spacing of 5.0 m × 3.0 m. Various physical and chemical characteristics of the experimental soil are given in Table 1.

Irrigation treatments

Irrigation water for a drip irrigation system was supplied from an irrigation canal. All irrigation system parameters were calculated according to Yıldırım (2005). Lateral pipes of 16 mm diameter with in-line pressure compensated emitters (emitter spacing 50 cm, discharge rate 4 l/h) were laid out on two sides of each tree as one lateral on each side. Each lateral was laid out 50 cm away from the tree trunk. To control water volume, one mini valve was installed at each lateral input.

Dielectric sensors (EC-5, Decagon Devices, Pullman, Washington USA) were used to measure soil moisture at soil depths of 30, 60, 90 and 120 cm before each irrigation in each treatment and replication. Effective root depth was considered to be 90 cm. In order to assess deep percolation below 0–90 cm effective root depth, soil water was monitored at 90–120 cm soil depth. One tree was selected for each replication, and an access tube was placed perpendicularly between the two lateral lines under the canopy of sweet cherry tree.

Full bloom dates of the 0900 Ziraat sweet cherry cultivar were April 18 in 2016, 21 April 2017, 10–11 April in 2018, and 24–25 April in 2019. By measuring the soil moisture after the full bloom period every year, when the soil water level at the effective root depth (0–90 cm) decreased to 40%, irrigation water was applied until available soil water at the effective root depth in all treatments reached the field capacity and subsequent irrigations were applied when the soil moisture decreased by 30%.

The current study consisted of six irrigation treatments: I_C, in with no deficit irrigation (where available water at effective root

Table 1. Soil characteristics of the experimental area

Depth (cm)	Field capacity (%)	Wilting point (%)	Bulk density (g/cm³)	Soil salinity (dS/m)	pH	Organic matter (%)	Texture
0–30	34.25	17.11	1.40	0.307	7.93	2.23	Clay loam
30–60	17.15	9.30	1.51	0.242	7.95	1.12	Sandy loam
60–90	20.5	12.37	1.50	0.285	7.90	1.90	Sandy clay loam
90–120	44.4	23.34	1.29				Clay loam

depth) was brought up to field capacity in each irrigation); I_{25}, with non-deficit irrigation till harvesting and 25% deficit irrigation after harvest, I_{50}, with non-deficit irrigation till harvest and 50% deficit irrigation after harvest, I_{25BH}, with non-deficit irrigation 30 days after full bloom and 25% deficit irrigation after this period (including Stage III of fruit development), I_{50BH}, with non-deficit irrigation 30 days after full bloom and 50% deficit irrigation after this period (including Stage III of fruit development), I_{FRM}, with farmer's treatment of non-deficit irrigation after full bloom till fruit colouring, using excessive irrigation (150% of ET) from colouring sweet cherry till harvest (Stage III of fruit development) and 50% deficit irrigation after this period to the end of the growing period (Fig. 1). I_{FRM} treatment was conducted according to the sweet cherry growers' practice (Yıldız et al., 2021). Sweet cherry growers apply irrigation in excess of requirements during the pre-harvest period and apply uncontrolled water deficit after harvest. Therefore, it was called farmer's treatment (I_{FRM}). Sweet cherry has a clear separation of physiological stages: first rapid growth stage (cell division and enlargement) (Stage I), pit hardening (Stage II), and second rapid growth stage (colouring of fruit and cell enlargement) (Stage III) (Azarenko et al., 2008).

Irrigation water (I), evapotranspiration (ET) and water productivity (WP)

Irrigation water (I) was calculated in each treatment according to Eqn (1) (Kanber, 2002). The amount of water calculated for I_c was considered to determine the amount of irrigation water for other deficit irrigation treatments.

$$I = [(Pw_{FC} - Pw)/100] \times D \times \gamma \times P \qquad (1)$$

In Eqn (1), I, is the amount of irrigation water (mm); Pw_{FC} is soil moisture content at field capacity (cm^3/cm^3) at the effective root zone (mm), Pw is the soil moisture content before each irrigation (cm^3/cm^3) at the effective root zone (mm) D Is the effective root depth (mm) γ is the soil bulk density: (g/cm^3), and P is the shaded area (40%). The percentage of the shaded area was calculated as the ratio of the shaded area to the total surface area of the orchard. A water meter was used for each irrigation treatment to measure the irrigation water volume.

		Months																			
	J	F	M	April			May			June			July			August			September	O	N	D
				I*	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III			
		Dormancy period		**Full bloom-fruit set period		Fruit development – Harvesting DAFB (Days After Full Bloom)				After harvesting period									Leaf fall	Dormancy period	
Treatments			The rate of applied water according to I_C treatment (%)																		
I_C			100																		
I_{25}			100				75														
I_{50}			100				50														
I_{25BH}			100			75															
I_{50BH}			100			50															
I_{FRM}			100			Excessive water (farmer treatment)	50														

Figure 1. Treatments in this current study. * I, II and III numbers state ten days of each month; **Full bloom period for each year ends between 13th and 20th in April except extreme climate conditions. Harvesting period is between 20th and 25th in June for each year except extreme climate conditions. There are average 60 days between end of the full bloom period and harvesting period. Time periods in this table are the results of the climate data of long period and surveys of growth periods in sweet cherry trees (0900 Ziraat cultivar); I_c, no deficit irrigation; I_{25}, non-deficit irrigation till harvesting, 25% deficit irrigation in comparison with the control after harvesting; I_{50}, non-deficit irrigation till harvesting, 50% deficit irrigation after harvesting; I_{25BH}, non-deficit irrigation 30 days after full bloom, 25% deficit irrigation after this period; I_{50BH}, non-deficit irrigation 30 days after full bloom, 50% deficit irrigation after this period; I_{FRM}, farmer treatment, non-deficit irrigation after full bloom till colouring sweet cherry, excessive irrigation (150% of ET) from colouring sweet cherry till harvest and 50% deficit irrigation after this period to end of the growing period.

Evapotranspiration (ET) was calculated by using soil the water balance method (Eqn ([2](#)); James [1988](#)).

$$ET = I + R + Cr - Dp - Rf \pm \Delta s \qquad (2)$$

In Eqn ([2](#)), ET is the evapotranspiration (mm), I, is the amount of irrigation water (mm), R is the precipitation (mm), Cr is the capillary rise (mm), Rf is the surface run-off (mm), Dp is the water loss by deep percolation (mm), and Δs is the change in profile soil water content (mm).

Cr and Rf were considered to be zero because the current study area had no ground water problem and the emitter discharge rate on the lateral pipes was determined to be compatible with the infiltration rate. The soil water sensors were placed to measure deep percolation (Dp) below the effective root zone depth (90–120 cm). Δs is the change in the soil water storage in 90 cm soil depth at planting and at harvest (mm). Precipitation was measured after every rainy day by using a pluviometer which was near the cherry orchard.

Equation [3](#) was used to calculate WP for all treatments (Mali, [2016](#)).

$$WP = Yield(kg/ha)/ Total irrigation applied(m^3/ha) \qquad (3)$$

where WP is the water productivity (kg/m^3), Y is the yield (kg/ha), and I is the irrigation amount applied over the season (m^3/ha).

Other measurements

Yield and fruit quality

For harvesting, five trees were selected in the middle of each experimental plot and all fruits were weighed (t/ha). Dates of harvest were June 21 in 2016, June 22 in 2017, June 12 in 2018, and June 22 in 2019.

The analysis of the physical properties (fruit size, flesh firmness and fruit skin colour) and chemical properties (soluble solids content, SSC) of the fruit were analysed to determine the fruit quality ([Table 2](#)). The distance between the two opposite sides of the fruit was measured to determine fruit size. Measurements were made using a digital caliper of 0.01 mm resolution (Vernier Caliper, Germany). Flesh firmness (FF) was measured on all single fruits at two diametrically opposite locations on the cheeks of each fruit (penetrometer with a tip of 5 mm). A texture analyser (Güss FTA Type GS14 Fruit-Texture Analyser Model, Strand, South Africa) was used in the measurement and the data obtained were expressed in Newton (N). One hundred fruits from one tree for each plot were used for measurements

of fruit size and FF analysis. For determining SSC, 30 fruits, whose seeds were separated, were crushed for each treatment, using a juicer to obtain fruit juice. Some fruit juice was dropped into the ocular part of the digital refractometer (HANNA Instruments) and the reading was performed (%). Fruit skin colour measurements were made on 30 fruits for each plot by using a Minolta CR-400 (Konika Minolta Inc., Japan) chromometer device equipped with a 5 mm measuring head and observer 10° and illuminant D65. The meter was calibrated using the manufacturer's standard white plate and the colour changes were quantified in the $L^\star$, $a^\star$ and $b^\star$ colour spaces. The hue° angle ([h° = tan -1 [$b^\star/a^\star$] $+ 180°$] was calculated when $a^\star < 0$ and $b^\star > 0$) and chroma values ($C = [a^\star 2 + b^\star 2]1/2$) were calculated from the $a^\star$ and $b^\star$ values. The hue values refer to a colour wheel. The red, yellow, green, and blue colours were at angles of 0°, 60°, 120° and 240°, respectively. Brightness ($L^\star$), red – green ($a^\star$) and yellow – blue ($b^\star$), hue angle (h) and chroma ($C^\star$) values were measured and hue° was used to evaluate the colour.

Leaf water potential (Ψ_{md})

A pressure chamber was used to measure leaf water potential in the field (PMS Instrument Company, Model 1000, USA). The measurements were carried out in one tree selected from each replication by using the method of midday leaf water potential (Ψ_{md}). At least five leaves per tree were used for Ψ_{md} measurements and the measurements were carried out between 12:00 and 14:00 on the day before irrigations. Leaf samples were collected from the sun-exposed mature leaves of one year old shoots from different sides of the selected trees in every treatment.

Stomata conductance (gsw)

A porometer (Delta-T, Porometer-AP4, United Kingdom) was used to measure stomata conductance (g_{sw}) on trees. g_{sw} measurements were carried out simultaneously with Ψmd measurements on the same trees. At least five leaves were used for g_{sw} measurements per sweet cherry tree and two repetitive readings were carried out on each leaf.

Trunk cross sectional area

Covariance analysis was made for trunk diameter. Trunk diameter (cm) was measured for all the sweet cherry trees in the dormancy period (February) using a digital caliper. Trunk diameter was measured on east-west and north-south orientations at 20 cm above the graft point and the average of the two values was calculated and taken as the trunk diameter. Equation [4](#) was used to calculate trunk cross-sectional area.

$$Trunk\ cross\ sectional\ area = \pi \times (trunk\ diameter/2) \qquad (4)$$

where trunk cross sectional area (TCSA) is in cm^2, and trunk diameter (cm) is the diameter of the tree trunk.

Shoot growth

One-year shoots from the main branch were selected for each tree per replication, and the lengths of shoots were measured (cm) with digital calipers in the dormancy period (February).

Experimental design and statistical analysis

It was observed that there was a unidirectional heterogeneous soil structure in the field. For this reason, it was concluded that it was suitable to conduct the current study in a Randomized Block

Table 2. Fruit quality parameters and measurements

Parameters	Unit	Measurements
Fruit size	mm	Digital caliper was used with 0.01 mm resolution
Flesh firmness (FF)	N	Determined on two opposite sides of each fruit, using texture analyser instrument fitted with a 5 mm diameter probe
SSC	%	LCD digital bench refractometer
Fruit skin colour	hue°	Chroma meter -Minolta CR-400 (Konika Minolta Inc., Japan)

(a)

1.Replication	I_C	I_{25BH}	I_{25}	I_{FRM}	I_{50BH}	I_{50}
2.Replication	I_{25}	I_{50BH}	I_{50}	I_{25BH}	I_C	I_{FRM}
3.Replication	I_{50}	I_{FRM}	I_{50BH}	I_{25}	I_{25BH}	I_C

(b)

X	X	X	X	X	X	X
X	X	X	X	X	X	X
X	X	X	X	X	X	X

Figure 2. Experimental design (a) and layout of the individual treatments (b) (X: sweet cherry tree) (grey coloured: considered trees for all measurements and harvesting in each replication).

Experimental Design (Fig. 2). The blocks were created perpendicular to the heterogeneous soil structure. Each treatment had three replications and there were three rows in each replication, with seven trees in each row. Thus, there were twenty-one sweet cherry trees in three rows in each replication. Only five trees in the middle of the rows were considered for calculating yield and to do the other measurements. Therefore, all measurements and harvests were conducted on five trees in each replication. The analysis of variance test was conducted with JMP software (SAS Institute, 2002) for the data. The differences among treatments were compared by using the least square difference (LSD)

method. The homogeneity of variances was tested to combine the years in the conducted experiment. Test results showed that the variances were not homogeneous. For this reason, years were evaluated separately.

Results

Irrigation water and evapotranspiration

The seasonal average temperature fluctuated during the growing season of the sweet cherry trees, between May and October (Fig. 3). The highest average temperature values were obtained
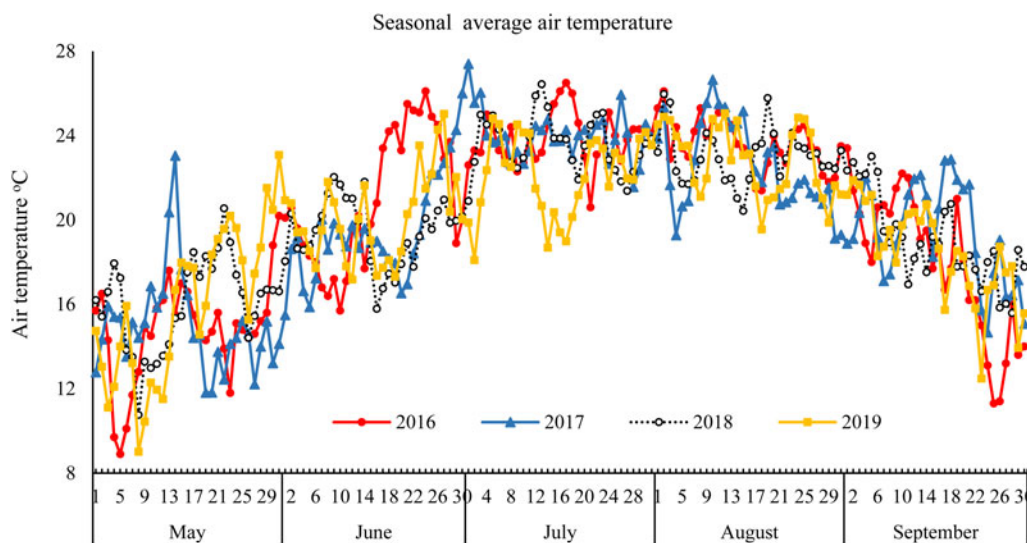

Figure 3. Seasonal daily average air temperature of the experimental area.

in July and August. The available water at the effective root depth of the sweet cherry trees in the I_C treatment was maintained at field capacity for each irrigation. I and ET were higher in 2016 and 2018 than in the other years (Table 3). The reason for this may be that the average temperature in the growing period in 2016 and the yield in 2018 were higher than in the other years. I and ET for all treatments fluctuated according to water deficit rates and application periods.

The soil water content (SWC) for all treatments was measured at 0–90 cm soil depth before each irrigation in the current study (Fig. 4). SWC at the effective root zone fluctuated during the growing season for all experiment years. When it rained during the growing season, SWC in the I_C treatment exceeded field capacity and then deep percolation occurred. In other treatments, SWC exceeded field capacity on rainy days when irrigation water was applied to reach field capacity. SWC decreased especially after harvest. The reason for this decreased SWC may be associated with increasing air temperature and high ET in the summer months. The highest I and ET were determined in the I_C treatment in the current study years because no deficit irrigation was applied.

Irrigation water saving was obtained at different rates when deficit irrigation was applied. When compared to I_C, deficit irrigation provided water savings ranging from 20.2 to 41.6% in 2016, from 22.5 to 39.7% in 2017, from 20.2 to 43.9% in 2018 and from 20.7 to 45.6% in 2019.

Yield and fruit quality

Sweet cherry fruit yield and various fruit quality parameters for the different treatments in the experimental years are presented in Table 4. The statistical analysis of the yield and various quality parameters are summarized in Table 5. Yield was not significantly different amongst the treatments in 2016 (Table 4). However, irrigation treatments resulted in significantly different yields in the 2017 ($P < 0.05$), 2018 ($P < 0.05$) and 2019 ($P < 0.01$) growing seasons. Due to low air temperature in 2017 when the sweet cherry trees were blooming (Fig. 3), yield was lower than in the previous year. The fruit yield was similar in the I_C and I_{25} treatments. The 50% water deficit application decreased yield in all experimental years. Cumulative yield data are shown in Fig. 5. The highest cumulative yield was obtained for the I_C and I_{25} treatments,

54.9 and 54.8 t/ha, respectively. I_{50BH} treatment had the lowest cumulative yield of 37.9 t/ha. It was determined that cumulative yield differences among treatments increased after the first year.

Fruit size was affected by water deficit ($P < 0.05$ for 2017 and 2019, $P < 0.01$ for 2018) except for the first year (Table 4). As water deficit was applied to the sweet cherry trees in I_{25BH} and I_{50BH} treatments for a short period before harvesting (Stage III of Fruit Development), their fruit size was smaller than for the other treatments. In 2019, fruit size was negatively affected also for I_{50}. Fruit size was higher under I_{FRM} compared with most of the deficit irrigation treatments but did not exceed the results found with I_C and I_{25}.

With the water deficit applied to the sweet cherry trees in I_{25BH} and I_{50BH} for a short period during the first year before harvest, FF in these treatments was significantly increased ($P < 0.05$ for 2016 and $P < 0.01$ for other experiment years) in comparison with to the other treatments (Table 5). Fruit flesh firmness of the 0900 Ziraat sweet cherry cultivar was affected by water deficit even if the water deficit period was short (Table 4). Lower FF results were obtained with the I_{25} and I_{50} (water deficit applied after harvest), I_C (no water deficit) treatments, and with I_{FRM}.

The total SSC of sweet cherry was similar among the treatments in 2017 (Table 4). In the following years, the SSC with I_{50BH} and I_{25BH} treatments tended to be higher than with I_{25} and I_{FRM}. Deficit irrigation treatments had no effects on the hue° of any fruits in the first year. Water deficits (I_{25BH} and I_{50BH}) applied just before harvesting affected hue° positively (Table 4). I_4 (water deficit of 25% applied just before harvesting) had the highest hue° value. Farmer treatment (I_{FRM}) had no positive effect on hue°, as the farmers claimed.

Water productivity

Water productivity measurements fluctuated according to the water deficit period in the treatments (Fig. 6). WP ranged between 1.07 and 1.59 kg/m³ in 2016 and the lowest WP was seen in I_C. WP ranged between 1.05 and 1.30 kg/m³ in the second year of the experiment. I_{25BH} had the highest value with 1.30 kg/m³. In 2017, treatment I_{50BH} had the lowest WP in 2017. WP also increased with increasing yield in 2018 and 2019. In the final year, to which water deficit was applied after harvesting had the highest WP with 4.86 and 4.53 kg/m³ for I_{25} and I_{50}, respectively.

Table 3. Total amount of water (I, mm), evapotranspiration (ET, mm) and precipitation (P, mm) (May 1–Sept. 30) during the current study

Treatments	2016		2017		2018		2019	
	I	ET	I	ET	I	ET	I	ET
I_C	721.4	795.5	649.6	739.6	703.2	808.9	687.6	797.9
I_{25}	575.9	643.9	503.7	557.7	561.2	725.5	545.6	670.8
I_{50}	422.9	514.9	426.7	496.1	419.3	625.2	395.4	563.6
I_{25BH}	510.2	612.6	423.8	501.3	518.7	647.1	515.7	657.4
I_{50BH}	421.6	533.8	391.9	451.4	394.3	559.8	373.8	493.5
I_{FRM}	493.3	537.5	466.6	513.6	496.3	593.9	481.0	554.2
Precipitation	94.6		105.5		144.0		106.4	

I_C, no deficit irrigation; I_{25}, non-deficit irrigation till harvesting, 25% deficit irrigation in comparison with the control after harvesting; I_{50}, non-deficit irrigation till harvesting, 50% deficit irrigation after harvesting; I_{25BH}, non-deficit irrigation 30 days after full bloom, 25% deficit irrigation after this period; I_{50BH}, non-deficit irrigation 30 days after full bloom, 50% deficit irrigation after this period; I_{FRM}, farmer treatment, non-deficit irrigation after full bloom till colouring sweet cherry, excessive irrigation (150% of ET) from colouring sweet cherry till harvest and 50% deficit irrigation after this period to end of the growing period.
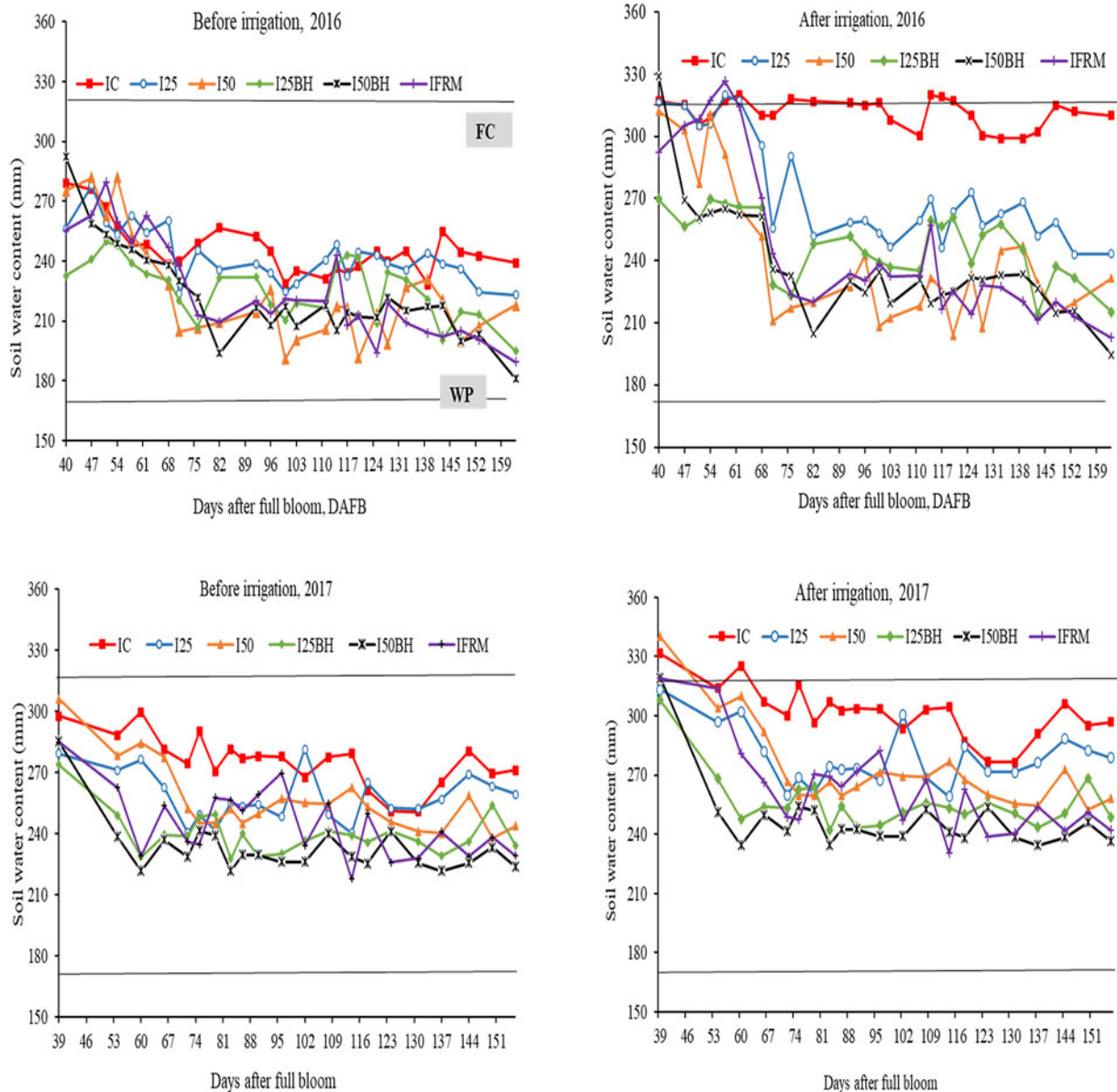
Figure 4. The soil water content at initiation and after irrigations during experiment period in 2016, 2017, 2018 and 2019. FC, field capacity; WP, Wwilting point.

Leaf water potential (Ψ_{md})

Leaf water potential (Ψ_{md}) decreased generally towards the end of the growing season for all years (Fig. 7). Statistical analyses were made for each measurement date, and the results are shown on the graphs. There were more differences among treatments in the last measurements on 27th of September in 2017, 27th of September in 2018, and 17th of September in 2019. Water deficit applications in different periods affected Ψ_{md} at different rates. Ψ_{md} values ranged from −1.5 to −2.4 MPa in 2017, from −1.4 to −2.5 MPa in 2018 and from −1.6 to −2.6 MPa in 2019. Ψ_{md} decreased in deficit irrigation treatments according to water deficit rates and application periods. No deficit irrigation treatment (I_C) had the highest Ψ_{md} results. The Ψ_{md} of the sweet cherry trees responded quickly to water deficit applications. The trees were negatively affected by the water deficit applications, even if the applications lasted for short periods of time. The Ψ_{md} in the water deficit applied at 25% after harvest was closer to I_C

during all project periods. The lowest Ψ_{md} results were determined in treatments I_{50BH} and I_{25BH} which had longer water deficit periods, starting from pre-harvest to the end of the growing period.

Stomata conductance (g_{sw})

Water deficit applications in different growing periods affected g_{sw} and statistical analyses were conducted for all measurement dates ($P < 0.01$ and $P < 0.05$). g_{sw} decreased generally towards the end of the growing season (Fig. 8). g_{sw} ranged from 78.0 to 184.8 in 2017, from 88.9 to 167.0 in 2018 and from 84.9 to 160.0 mmol/m²/s¹ in 2019. I_C treatment had the highest g_{sw} for all measurements. Also, I_{25} had higher g_{sw} in comparison with the other irrigation treatments close to that found with I_C. Statistical differences among treatments according to g_{sw} results were mostly detected in the last two measurements on 25th of August and 12th of
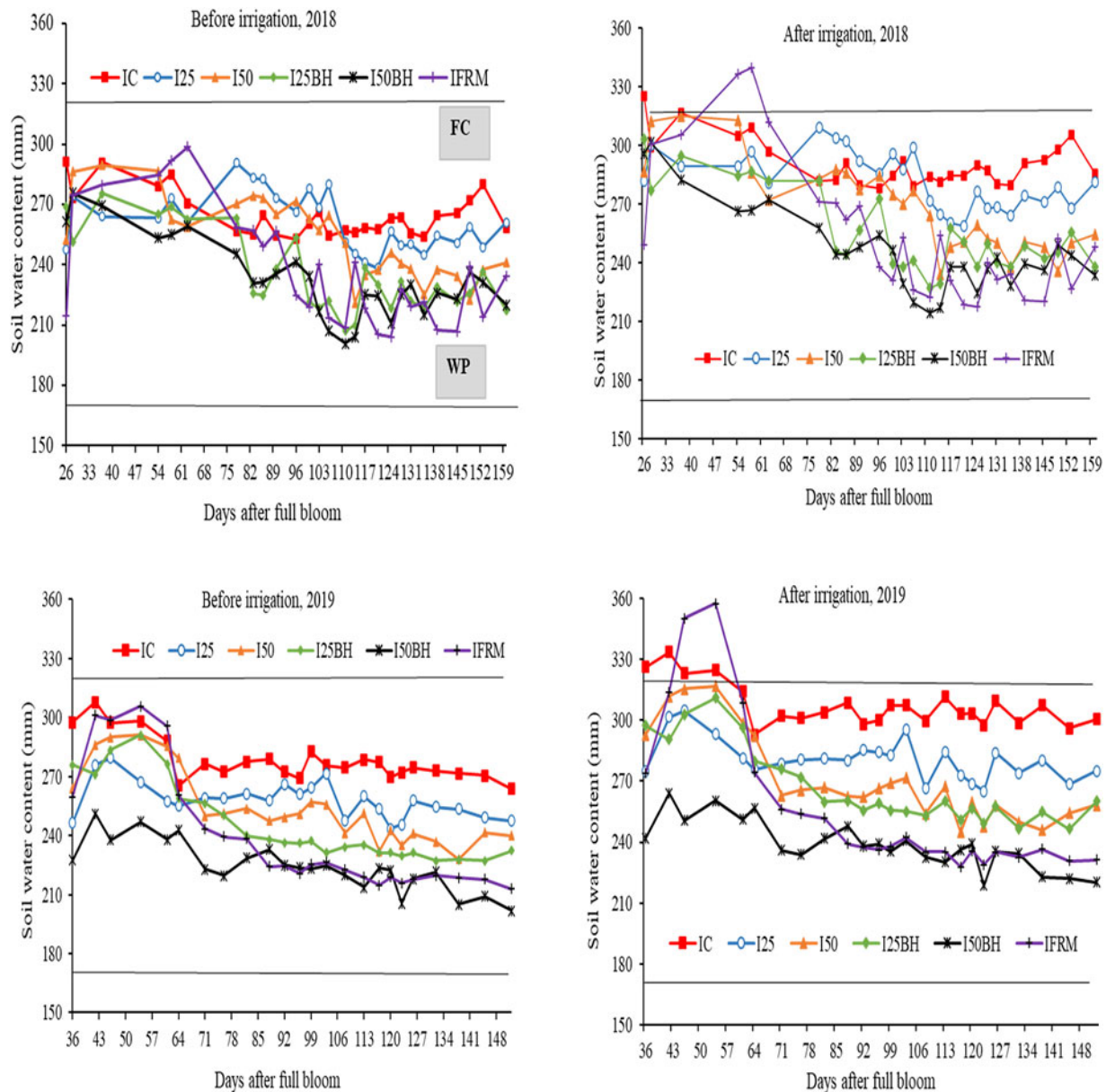
Figure 4. Continued.

September in 2017, 25th of August and 17th of September in 2018, and 24th of August and 17th of September in 2019. I_{50BH} and I_{FRM} treatments had the lowest values with 50% water deficit applied. The data suggest that 25% water deficit had no negative effect on the g_{sw} of the sweet cherry trees.

Trunk cross sectional area

TSCA increased for all treatments during the experiment even when water deficit was applied (Table 4). TSCA was found to be statistically significant ($P < 0.01$ for 2018 and $P < 0.05$ for the other experiment years) (Table 5). The results indicate that the sweet cherry trees continued to grow despite water deficit applications. A higher increase of trunk cross section area was found with I_C and I_{25} relative to the other treatments. The TSCA grew the least for the trees in the I_{50BH} treatment (50% water deficit).

Shoot growth

The differences resulting from the treatments were recorded (Table 4). In 2016, the statistical differences were found not to be significant (Table 5). During the first year of the current study, shoot growth was not affected by deficit irrigation applications. I_{FRM} treatment, consisting of excessive water application, had the lowest shoot development.

Discussion

RDIs saved from 20.2 to 45.6% of irrigation water over the whole experiment. The farmer's application (I_{FRM}) also saved between 28.2 and 31.7% of irrigation water. Blanco et al. (2019) found that deficit irrigation (DI) in sweet cherry trees saved the greatest amount of water (39%) over the whole experiment compared with the control treatment (no deficit irrigation). It is common for

Table 4. Sweet cherry yield, fruit size, fruit flesh firmness (FF), SSC, skin colour, hue°, TSCA and shoot growth under different treatments in 2016, 2017, 2018 and 2019

Years	Treatments	Yield (t/ha)	Fruit size (mm)	Fruit flesh firmness (N)	SSC (%)	Skin colour hue°	TCSA (cm²)	Shoot growth (cm)
2016	I_C	7.8 ns	25.5 ns	10.0 bc*	17.6 ns	15.6 ns	159.4 a*	36.6 ns
	I_{25}	7.0	25.0	10.4 ab	17.9	14.9	157.8 a	40.2
	I_{50}	6.8	25.3	9.8 c	17.3	14.8	148.5 ab	34.8
	I_{25BH}	7.0	24.8	10.6 ab	17.6	11.5	142.0 b	37.1
	I_{50BH}	6.6	23.8	10.6 a	17.7	15.0	141.1 b	36.7
	I_{FRM}	7.4	25.7	10.3 ab	17.1	15.7	137.9 b	31.6
2017	I_C	6.9 a*	27.5 a*	14.9 b**	16.4 ab*	28.7 bc**	230.3 a*	34.9 bc*
	I_{25}	5.9 ab	27.2 ab	15.1 b	15.9 bc	27.6 c	224.1 a	36.3 ab
	I_{50}	4.9 bc	27.2 ab	15.3 b	16.2 ab	30.1 b	213.6 ab	37.1 ab
	I_{25BH}	5.5 b	26.9 bc	15.3 b	16.6 a	29.9 b	210.9 ab	40.0 a
	I_{50BH}	4.1 c	26.8 c	17.4 a	16.7 a	34.2 a	208.3 ab	36.2 ab
	I_{FRM}	5.2 bc	27.3 ab	15.1 b	15.4 c	31.0 b	187.6 b	30.9 c
2018	I_C	18.5 a*	26.5 a**	11.9 b**	16.7 ab*	25.2 bc**	286.9 a**	34.9 b**
	I_{25}	15.3 ab	26.8 a	12.1 b	16.4 bc	24.2 cd	277.1 a	36.3 ab
	I_{50}	12.4 b	26.4 ab	12.2 b	16.6 ab	24.6 bcd	276.1 a	37.1 ab
	I_{25BH}	14.5 ab	25.3 b	13.6 a	16.9 ab	26.8 a	267.2 ab	40.0 a
	I_{50BH}	10.5 b	24.7 c	13.4 a	17.3 a	26.0 ab	245.7 b	36.2 b
	I_{FRM}	12.0 b	26.8 a	12.2 b	15.8 c	23.6 d	249.6 b	30.9 c
2019	I_C	21.8 b**	26.8 a*	13.7 c**	13.5 b**	26.3 b*	337.9 a*	34.3 b*
	I_{25}	26.5 a	26.9 a	14.0 c	13.4 b	25.8 b	326.7 ab	33.6 b
	I_{50}	17.9 cd	25.7 c	14.2 bc	13.5 b	26.6 b	300.2 abc	40.0 a
	I_{25BH}	20.8 bc	26.2 bc	14.8 ab	14.7 a	28.2 a	285.6 bc	38.4 ab
	I_{50BH}	16.6 d	25.8 c	15.2 a	14.9 a	25.6 b	279.6 c	34.3 b
	I_{FRM}	18.8 bcd	26.7 ab	14.0 c	13.8 b	26.1 b	275.2 c	28.3 c

I_C, no deficit irrigation; I_{25}, non-deficit irrigation till harvesting, 25% deficit irrigation in comparison with the control after harvesting; I_{50}, non-deficit irrigation till harvesting, 50% deficit irrigation after harvesting; I_{25BH}, non-deficit irrigation 30 days after full bloom, 25% deficit irrigation after this period; I_{50BH}, non-deficit irrigation 30 days after full bloom, 50% deficit irrigation after this period; I_{FRM}, farmer treatment, non-deficit irrigation after full bloom till colouring sweet cherry, excessive irrigation (150% of ET) from colouring sweet cherry till harvest and 50% deficit irrigation after this period to end of the growing period.
Different lowercase letters indicate significant differences. **LSD grouping at $P < 0.01$ level; *LSD grouping at $P > 0.05$; ns, not significant.

sweet cherry growers to apply an uncontrolled water schedule (less water than required for sweet cherry trees) during the post-harvest period coinciding with summer in the Mediterranean region (Blanco *et al.*, 2019). Available water resources have decreased in recent years because of drought and lack of precipitation. This decrease is more pronounced in the Mediterranean Region and causes severe water shortage. (Lo Bianco *et al.*, 2012). Regulated deficit application is becoming more important in dry climates such as the Mediterranean region. Therefore, the results are currently relevant and important, and will be especially so in the future, with increasing water shortages caused by ongoing climate change. Sweet cherry growers can use these treatments in areas where water resources are scarce. On the other hand, any one of the deficit treatments tested in this current study can be applied for water savings by sweet cherry growers depending on the targets for fruit yield and fruit quality desired by the grower.

Deficit irrigation treatments did not affect sweet cherry fruit yield in the first year of the experiment. The reason may be that sweet cherry harvesting was early in the season and it was the first year of the current study. The harvesting date was only approximately six weeks after the first irrigation date. Due to low air temperatures when the sweet cherry trees were blooming in 2017 (Fig. 3), yield was lower than in other years. Sweet cherry trees in treatments I_C and I_{25} had the highest yield during the current study except in 2016. Both water deficit rates and the water deficit treatments applied before and after harvest had different effects on yield. Yield in treatments applying 25% water deficit (I_{25} and I_{25BH}) was higher in comparison with 50% water deficit treatments (I_{50} and I_{50BH}). Also, yield was higher in treatments in which water deficit was applied before harvest more than in treatments applied after harvest even if the same water deficit rates were applied. Extreme weather conditions and/or water deficits applied during the trees' productive cycle might affect their

Table 5. Statistical analysis results of yield, fruit size, fruit flesh firmness (FF), SSC, skin colour, hue°, TCSA and shoot growth under different treatments in the experimental years

Years	Statistical analysis	Yield (t/ha)	Fruit size (mm)	Fruit flesh firmness (N)	SSC (%)	Skin colour hue°	TCSA (cm²)	Shoot growth (cm)
2016	LSD 0.05	ns	ns	0.36	ns	ns	15.20	ns
	Probability	ns	ns	0.0001*	ns	ns	0.0166*	ns
	CV (%)	ns	ns	9.2	ns	ns	11.2	ns
2017	LSD 0.05	0.497	0.35	0.95	0.5	2.25	26.60	4.89
	P (Probability)	0.0001*	0.0031*	0.0001*	0.0052*	0.0030*	0.0495*	0.0464*
	CV (%)	12.6	4.4	9	1.7	4.1	10.2	10.4
2018	LSD 0.05	2.65	0.52	0.39	0.83	1.53	24.6	5.1
	Probability	0.0001*	0.0001*	0.0001*	0.0655*	0.0152*	0.0142*	0.0233*
	CV (%)	10.4	6.5	3.2	2.8	3.4	9.7	10.8
2019	LSD 0.05	3.81	0.46	0.73	0.89	1.60	43.83	4.9
	Probability	0.0001*	0.0001*	0.0177*	0.0223*	0.0516*	0.0438*	0.0454*
	CV (%)	11.6	6.5	2.8	3.5	3.31	10.4	10.6

LSD, least significant difference; CV, coefficient of variation.
**LSD grouping at $P < 0.01$ level; *LSD grouping at $P > 0.05$; ns, not significant.

response in the following year (transportation effect). The effect of water deficit on the yield of temperate fruit trees, such as sweet cherry, could be felt in subsequent years (Doorenbos *et al.*, 1986). It is a requirement to know all the effects of deficit irrigation on the flowering of the current and following years; also, on flower bud's development, fruit and leaf area growth, fruit setting and the physiological process when a water deficit is applied (Blanco *et al.*, 2020). Excessive water applications had a negative effect on flower development and could cause a decrease in fruit setting and yield in the following year (Goldhamer and Shackel, 1990). Marsal *et al.* (2009) reported that 20 and 50% water deficit applications increased yield compared to a control (no deficit irrigation) treatment. The reason for these results may be that the experiment lasted only for a period of two years. Blanco *et al.* (2019) found that there was no significant effect of RDI on yield parameters. Water deficit rates and application periods used in that study were different from the current study. Treatment I_{25} gave similar results to the no deficit irrigation treatment (I_C) in terms of cumulative yield. It means that sweet cherry growers can apply 25% deficit irrigation water after harvesting when their only aim is maximum yield.
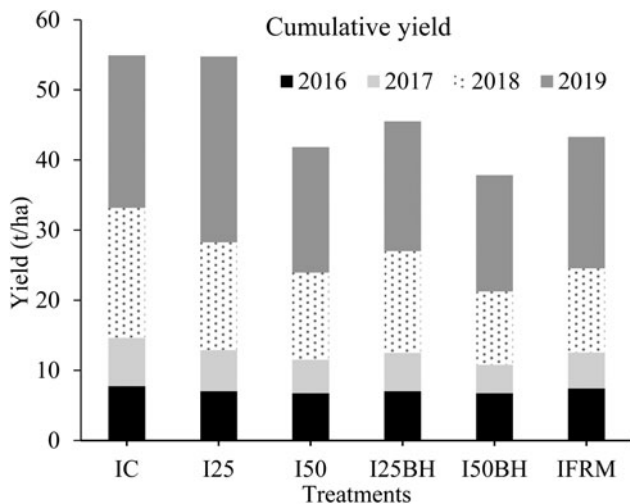

Figure 5. Cumulative yield of all treatments (t/ha). I_C, no deficit irrigation; I_{25}, non-deficit irrigation till harvesting, 25% deficit irrigation in comparison with the control after harvesting; I_{50}, non-deficit irrigation till harvesting, 50% deficit irrigation after harvesting; I_{25BH}, non-deficit irrigation 30 days after full bloom, 25% deficit irrigation after this period; I_{50BH}, non-deficit irrigation 30 days after full bloom, 50% deficit irrigation after this period; I_{FRM}, farmer treatment, non-deficit irrigation after full bloom till colouring sweet cherry, excessive irrigation (150% of ET) from colouring sweet cherry till harvest and 50% deficit irrigation after this period to end of the growing period.
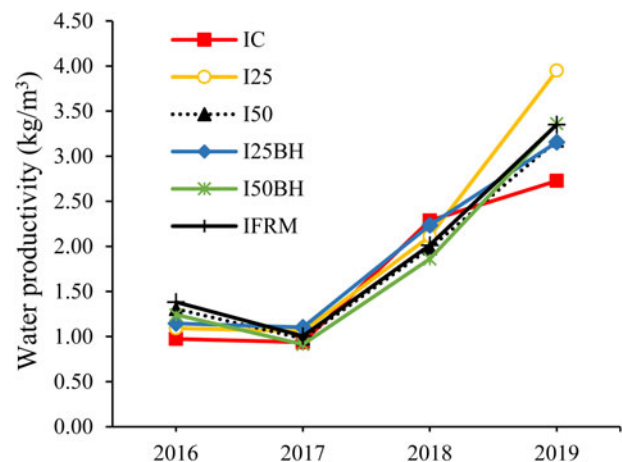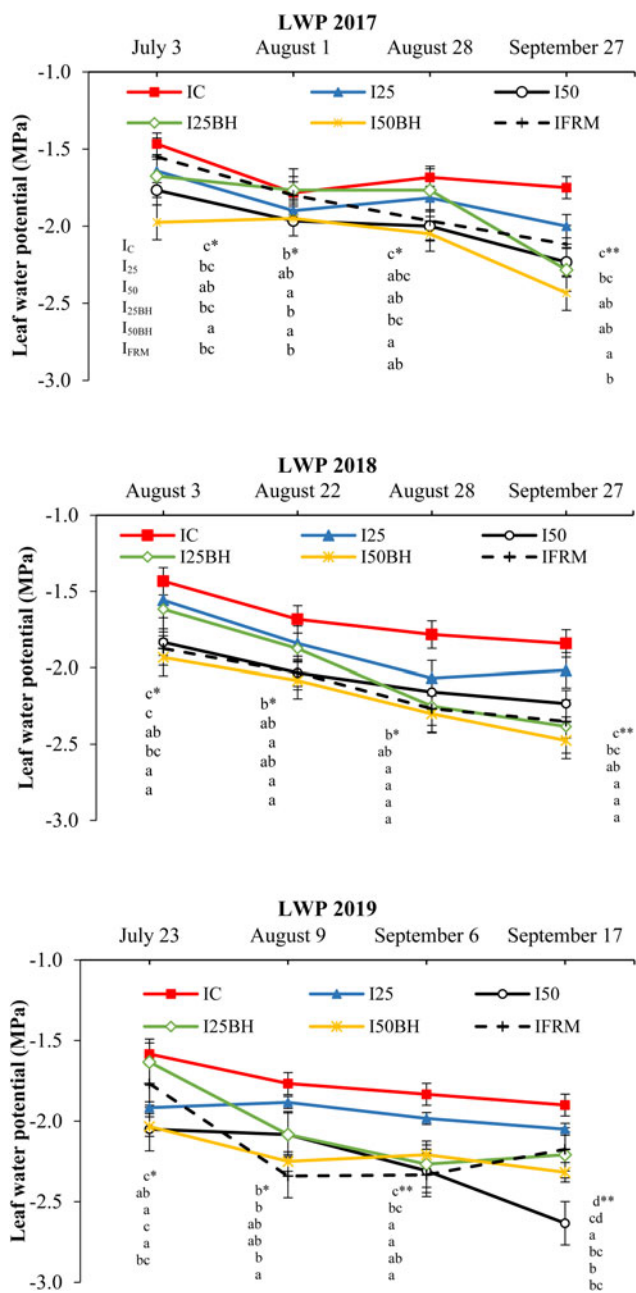

Figure 6. Water productivity (WP) of all treatments during the experimental years. I_C, no deficit irrigation; I_{25}, non-deficit irrigation till harvesting, 25% deficit irrigation in comparison with the control after harvesting; I_{50}, non-deficit irrigation till harvesting, 50% deficit irrigation after harvesting; I_{25BH}, non-deficit irrigation 30 days after full bloom, 25% deficit irrigation after this period; I_{50BH}, non-deficit irrigation 30 days after full bloom, 50% deficit irrigation after this period; I_{FRM}, farmer treatment, non-deficit irrigation after full bloom till colouring sweet cherry, excessive irrigation (150% of ET) from colouring sweet cherry till harvest and 50% deficit irrigation after this period to end of the growing period.

Figure 7. LWP measurements in 2017, 2018 and 2019. Error bars indicate standard errors of the means. The letters in the box show the statistical analysis results for each measurement date and the mean of each treatment, **LSD grouping at $P <$ 0.01 level; *LSD grouping at $P > 0.05$. I_C, no deficit irrigation; I_{25}, non-deficit irrigation till harvesting, 25% deficit irrigation in comparison with the control after harvesting; I_{50}, non-deficit irrigation till harvesting, 50% deficit irrigation after harvesting; I_{25BH}, non-deficit irrigation 30 days after full bloom, 25% deficit irrigation after this period; I_{50BH}, non-deficit irrigation 30 days after full bloom, 50% deficit irrigation after this period; I_{FRM}, farmer treatment, non-deficit irrigation after full bloom till colouring sweet cherry, excessive irrigation (150% of ET) from colouring sweet cherry till harvest and 50% deficit irrigation after this period to end of the growing period.

Figure 8. Stomata conductance measurements in 2017, 2018 and 2019. Error bars indicate standard errors of the means. The letters in the box show the statistical analysis of the results for each measurement date and the mean for each treatment. **LSD grouping at $P < 0.01$ level; *LSD grouping at $P > 0.05$. I_C, no deficit irrigation; I_{25}, non-deficit irrigation till harvesting, 25% deficit irrigation in comparison with the control after harvesting; I_{50}, non-deficit irrigation till harvesting, 50% deficit irrigation after harvesting; I_{25BH}, non-deficit irrigation 30 days after full bloom, 25% deficit irrigation after this period; I_{50BH}, non-deficit irrigation 30 days after full bloom, 50% deficit irrigation after this period; I_{FRM}, farmer treatment, non-deficit irrigation after full bloom till colouring sweet cherry, excessive irrigation (150% of ET) from colouring sweet cherry till harvest and 50% deficit irrigation after this period to end of the growing period.

There are many factors that need to be considered in the terms of fruit quality in sweet cherry. Fruit size is one of the most effective parameters on yield. Fruit size is the most important factor in the marketing of cherries. There is a price difference between fruit size classes. Irrigation applications have a great effect on fruit diameter in addition to colour and other fruit quality parameters
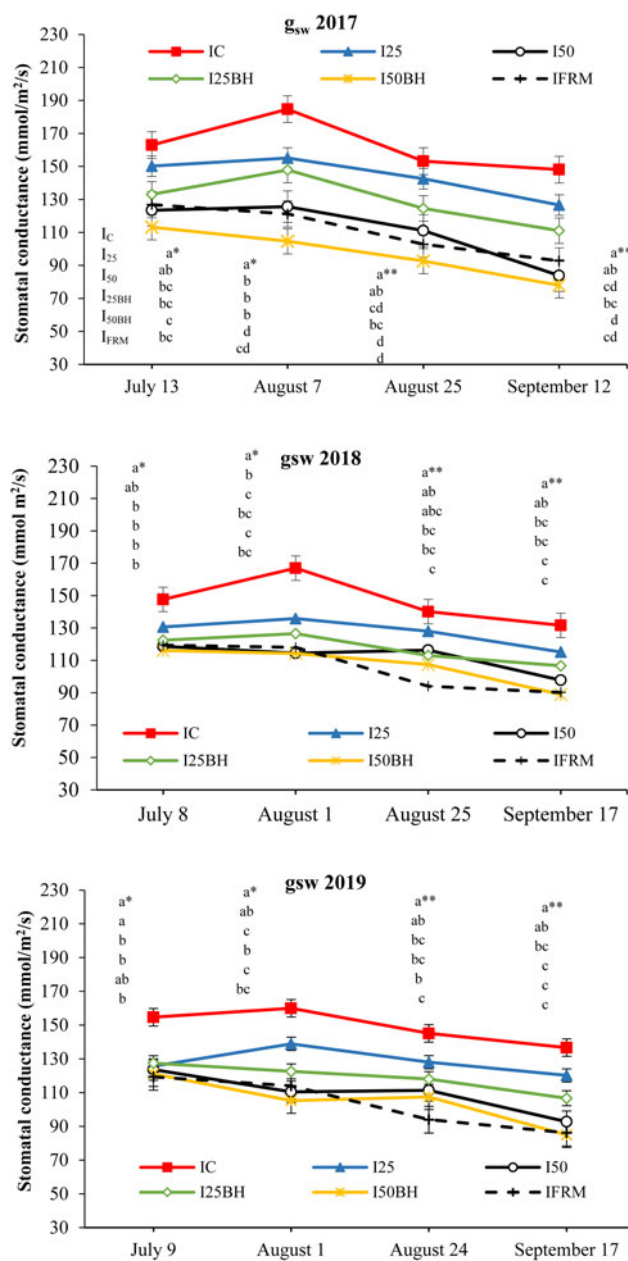
(Yıldız *et al.*, 2021). A grower producing large fruits can earn more money even if another grower has the same fruit yield. In 2017, yield was lower than in other years due to frost. Fruit size may be bigger than when yield is low than in years with an average yield. In the current study, the critical threshold for the fruit size of the 0900 Ziraat cultivar was achieved with 50% of water

deficit. I_{25} provided the greatest fruit size among the water deficit treatments. The fruit size obtained from treatment I_{FRM} (excessive irrigation water applied before harvesting) was close to the yield obtained from the no deficit irrigation treatment (I_C). This is an important result, but it should be considered with FF results which are important for marketing, transporting and storage. Water deficit treatments applied before harvesting (I_{25BH} and I_{50BH}) decreased fruit size. If farmers have limited water resources, they should consider that fruit size will decrease when they apply these treatments. The fruits were smaller in treatments in which water deficit was applied during fruit cell enlargement (Blanco et al., 2019). Marsal et al. (2009) obtained the largest fruit size from 20% water deficit treatment. The reasons for the different results achieved in the current study may have been the use of different cultivar/rootstock combinations and a shorter experiment period than the current study.

Water deficit treatments applied before and after harvesting had different effects on flesh firmness (FF) and SSC (Table 4). Even though water deficit rates were different, water deficits applied before harvesting increased FF and SSC (I_{25BH} with 25% and I_{50BH} with 50%) more. I_{FRM} had a negative effect on FF and SSC, because excessive irrigation water was applied before harvesting. If sweet cherry is to be stored after harvesting, treatments I_{25BH} and I_{50BH} can be applied but less yield should be expected. These results can be considered for the storage and food industries of sweet cherry. The most marketable cherry (Prunus avium L.) fruits are defined as having high fruit firmness (Christensen, 1995; Kappel et al., 1996) and intense red skin colour (Crisosto et al., 2003). Sweet cherry growers need to consider the choice between – yield, FF or fruit size and they may apply one of the water deficit treatments according to the results of the current study. Water deficit treatments provided a higher SSC (Marsal et al., 2010; Blanco et al., 2022). Houghton et al. (2023) reported that PDI (postharvest deficit irrigations) did not affect SSC, but Marsal et al. (2009) found that SSC decreased in deficit irrigations applied after the harvest period. The reason for obtaining different results may be the use of different cultivar/rootstocks combinations and RDI applications in these studies. Water deficit applications starting just before harvest (I_{25BH}) increased hue° in the last two years (Table 4). The critical threshold for obtaining high hue° was water deficit applications for a short period before harvest, and the highest hue° was obtained when 25% water deficit was applied before harvest. Blanco et al. (2022) reported that deficit irrigation applied during the whole growing period negatively affected the hue° of sweet cherry. PDI (postharvest deficit irrigations) did not affect the fruit skin colour of sweet cherry fruits (Houghton et al., 2023). The reason for different results in comparison with the current study's results may be due to the water deficit applications in different growing periods and at different rates. WP increased more in 2018 and 2019 than in the other years of experiment (Fig. 6). The sweet cherry trees continued to growth and boosted their yield. Therefore, an increase in WP was noticed. All WPs were lower in 2017 than in other years because frost negatively affected yields. Treatment I_{25} had the highest WP in the last year of this experiment. WP in I_C was the lowest in 2019. The reason for the result may be that there were no water deficit applications. All deficit irrigation applications increased the WP of the sweet cherry trees, compared with the sweet cherry trees to which full irrigation applications were applied. Blanco et al. (2021) reported that in sweet cherry trees, the trees under deficit irrigation were those with the highest water productivity, and Ortega-Farias et al.

(2020) reported the same in hazelnut trees. These results are also consistent with those reported in other fruit trees subjected to reduced irrigation, such as nectarines (Prunus persica) and plums (Prunus salicina) (Conesa et al., 2019; Monino et al., 2020). When water resources are insufficient for irrigation, I_{25} treatment can be recommended in order to obtain the highest WP.

Ψ_{md} measurements made before sunrise and at midday are considered to be one of the best indicators for determining the water status of plants (Shackel et al., 1997; Ameglio et al., 1999). Due to decreasing tree water potential and soil water content in the rootzone area, Ψ_{md} was different in each treatment (Küçükyumuk et al., 2014; Blaya-Ros et al., 2021). Treatments I_C and I_{25} treatments were similar (Fig. 7.). A water deficit of 25% after harvest, I_{25}, did not negatively affect the Ψ_{md} of the trees. The decrease in Ψ_{md} was dramatic in I_{50BH}, in which 50% water deficit was applied from before harvesting to the end of the growing period. Applying excessive water before harvesting did not positively affect Ψ_{md}. Blaya-Ros et al. (2021) reported that the minimum mean Ψ_{md} values reached at the end of the first and second drought periods in moderate water stress v. severe water stress trees were −0.6 and −1.4 MPa (Ψ_{pd}), −2.2 and −3.1 MPa (Ψ_{md}) and −1.3 and −2.3 MPa (Ψ_{stem}), respectively, for the study period. Ψ_{md} results obtained from the current study were different because cultivar/rootstock and the ages of the trees were different. Since 50% water deficit decreased the soil water of the rootzone, the effect of water stress increased in I_{50} and decreased stomata conductance. Excessive water was applied to the sweet cherry trees in treatment I_{FRM} for a short period just before harvest, but 50% water deficit was applied to the sweet cherry trees in this treatment after harvesting. Consequently, g_{sw} decreased for all treatments towards the end of the growing period. Sweet cherry trees in I_{25} were affected less by water stress than the trees in other RDI treatments, according to g_{sw} results. The threshold for g_{sw} was determined as 25% water deficit applied after harvesting. When there is a decrease in soil water content at the effective root zone, this leads to water stress on plants (Mpelasoka et al., 2001; Küçükyumuk et al., 2015), and plants start to close stomata to decrease transpiration from the leaf surface. The closure of stomata may be regarded as a defence mechanism against dehydration (Rieger and Duemmel, 1992; Girona et al., 1993; Taiz and Zeiger, 1998).

Although water deficits were applied to the sweet cherry trees, their trunk growth increased between 195.0% and 212.0%. The longer water deficit period treatments of 25% and 50% (195.0% for I_{50BH} and 201.1% for I_{25BH}) decreased trunk growth. I_{25} was similar to I_C during the current study. This means that 25% water deficit applied after harvesting had no negative effect on TSCA. The most effective factors for growth of TCSA in sweet cherry trees are the volume of irrigation water and irrigation frequency (Neilsen et al., 2014). Some previous studies have reported that deficit irrigation negatively affected the trunk diameter of sweet cherry trees (Cohen et al., 2001; Yazgan et al., 2006). However, Blanco et al. (2019) reported that different SDI and RDI treatments did not affect TSCA during their four years study. The reason for the different results may be due to the treatments in the studies mentioned here having different rootstocks, cultivars, water deficit rates, and experimental periods. Water deficit treatments did not affect shoot length in the first year. The highest shoot length value was obtained in I_{25BH}, and the lowest in I_{FRM}. Although excessive water was applied for a short period in I_{FRM}, a 50% water deficit was applied for a longer period after

harvest. The longer period of water deficit negatively affected shoot length. Dehghanisanij *et al.* (2007) also reported that deficit irrigation had a negative impact on the length of shoots. Different application times and irrigation deficit rates had different effects on sweet cherry trees (Küçükyumuk *et al.*, 2013).

Conclusions

Mild water stress (I_{25}, 25% water deficit) applied after harvesting had a positive effect on yield and cumulative yield, the treatment did not negatively affect Ψ_{md} and g_{sw}. If sweet cherry growers are only interested in fruit size, they need to apply I_{25} (25% water deficit, mild water stress) after harvest. In addition, farmer treatment can also be applied for this purpose (I_{FRM}). Moderate water stress (50% water deficit) increased FF.

One of the deficit treatments mentioned in the current study can be applied to provide water saving by sweet cherry growers in similar climate conditions but yield and fruit quality need to be considered in the selection of the best treatment. Therefore, treatment I_{25} (25% water deficit after harvesting) can be applied by sweet cherry growers because it leads to a high yield, better fruit quality and water saving.

Author contributions. C. Küçükyumuk conceived and designed the study, conducted data gathering, performed statistical analyses and wrote the article.

Competing interests. None.

Ethical standards. Not applicable.

References

Ameglio T, Archer P, Cohen M, Valancogne C, Daudet FA, Dayau S and Cruiziat P (1999) Significance and limits in the use of predawn leaf water potential for tree irrigation. *Plant and Soil* **207**, 155–167.

Azarenko AN, Chozinski A and Brewer LJ (2008) *Fruit Growth Curve Analysis of Seven Sweet Cherry Cultivars.* Proceeding 5th International Cherry Symposium, June 2005, Acta Hortic. 795, pp. 561–566. doi: 10.17660/ActaHortic.2008.795.88

Blanco VM (2019) Agronomic and physiological basis for automating regulated deficit irrigation in sweet cherry trees. Universidad Politécnica de Cartagena, PhD Program in Advanced Techniques for Research and Development in Food and Agriculture, PhD thesis, 72 p.

Blanco V, Torres-Sanches R, Blaya-Ros TJ, Perez-Pastor A and Domingo R (2019) Vegetative and reproductive response of 'Prime Giant' sweet cherry trees to regulated deficit irrigation. *Scientia Horticulturae* **249**, 478–489.

Blanco V, Blaya-Ros PJ, Torres-Sánchez R and Domingo R (2020) Influence of regulated deficit irrigation and environmental conditions on reproductive response of sweet cherry trees. *Plants* **9**, 2–17.

Blanco V, Zoffoli JP and Ayala M (2021). Eco-physiological response, water productivity and fruit quality of sweet cherry trees under high tunnels. *Scientia Horticulturae* **286**, 110180.

Blanco V, Blaya-Ros PJ, Torres-Sánchez R and Domingo R (2022) Irrigation and crop load management lessen rain-induced cherry cracking. *Plants* **11**, 1–16.

Blaya-Ros PJ, Blanco V, Torres-Sánchez R and Domingo R (2021) Drought-adaptive mechanisms of young sweet cherry trees in response to withholding and resuming irrigation cycles. *Agronomy* **11**, 1–18.

Centritto M (2005) Photosynthetic limitations and carbon partitioning in cherry in response to water deficit and elevated [CO2]. *Agriculture, Ecosystems & Environment* **106**, 233–242.

Chockchaisawasdee S, Golding JB, Vuong QV, Papoutsis K and Stathopoulos CE (2016) Sweet cherry: composition, postharvest preservation, processing and trends for its future use. *Trends in Food Science and Technology* **55**, 72–83..

Christensen JV (1995) Evaluation of fruit characteristics of 20 sweet cherry cultivars. *Fruit Varieties Journal* **49**, 113–117.

Cohen M, Goldhamer D, Fereres E, Girona J and Mata M (2001) Assessment of peach tree responses to irrigation water deficits by continuous monitoring of trunk diameter changes. *The Journal of Horticultural Science and Biotechnology* **76**, 55–60.

Collins M, Knutti R, Arblaster J, Dufresne JL, Fichefet T, Friedlingstein P, Gao X, Gutowski WJ, Johns T, Krinner G, Shongwe M, Tebaldi C, Weaver AJ and Wehner M (2013) Long-term climate change: Projections, commitments and irreversibility. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, pp. 1029–1136. doi: 10.1017/CBO9781107415324.024

Conesa MR, Conejero W, Vera J, Ramírez-Cuesta JM and Ruiz-Sanchez MC (2019) Terrestrial and remote indexes to assess moderate deficit irrigation in early-maturing nectarine. *Trees. Agronomy* **9**, 630.

Crisosto CH, Crisoto GM and Metheney P (2003) Consumer acceptance of 'Brooks' and 'Bing' cherries is mainly dependent on fruit SSC and visual skin colour. *Postharvest Biology and Technology* **28**, 159–167.

de la Rosa JM, Domingo R, Gómez-Montiel J and Perez-Pastor A (2015) Implementing deficit irrigation scheduling through plant water stress indicators in early nectarine trees. *Agricultural Water Management* **152**, 207–216.

Dehghanisanij H, Naseri A, Anyoji H and Eneji AE (2007) Effects of deficit irrigation and fertilizer use on vegetative growth of drip irrigated cherry trees. *Journal of Plant Nutrition* **30**, 411–425.

Doorenbos J, Kassam AH, Bentvelsen CL, Branscheid M, Plusje V, Smith M, Uittenbogaard GO and Van Der Wal HK (1986) *Yield Response to Water.* FAO Irrigation and Drainage Paper. No: 33, 193 pp.

Ebel RC, Proebsting EL and Evans RG (1995) Deficit irrigation to control vegetative growth in apple and monitoring fruit growth to schedule irrigation. *HortScience* **30**, 1229–1232.

FAO (2017) *Water for Sustainable Food and Agriculture.* Food and Agriculture Organization of the United Nations, Rome, 2017, 27 p.

FAO (2021) *Sweet cherry production quantity.* Available online from: http://www.fao.org/faostat/en/#data/QCL (Accessed 7 August 2023).

Fereres E and Goldhamer D (1990) *Irrigation of Deciduous Fruit and Nut Trees.* In: Irrigation of Agricultural Crops. ASA Monograph No. 30. American Society of Agronomy, Madison, WI, pp. 987–1017.

Girona J, Mata M, Goldhamer DA, Johnson RS and DeJong TM (1993) Patterns of soil and tree water status and leaf functioning during regulated deficit irrigation scheduling in peach. *Journal of the American Society for Horticultural Science* **118**, 580–586.

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

Goldhamer DA and Shackel K (1990) Irrigation cutoff and drought irrigation strategy effects on almond. In Proceedings of the 18th Almond Research Conference, Fresno, CA, USA, December 1990, pp. 30–35.

Houghton E, Bevandicka K, Neilsenb D, Hannam K and Nelsona LM (2023) Effects of postharvest deficit irrigation on sweet cherry (*Prunus avium*) in five Okanagan Valley, Canada, orchards: II. Phenology, cold hardiness, fruit yield, and quality. *Canadian Journal of Plant Science* **00**, 1–17.

James LG (1988) *Principles of Farm Irrigation System Design.* New York, USA: John Wiley and Sons Inc.

Kanber R (2002) *Irrigation.* Çukurova University Agricultural Faculty Publishment No:174, Lecture Books Publishment No: A-52, Adana, Turkey, 530 p.

Kappel F, Fisher-Fleming B and Hogue E (1996) Fruit characteristics and sensory attributes of an ideal sweet cherry. *HortScience* **31**, 443–446.

Küçükyumuk C, Kaçal E and Yıldız H (2013) Effects of different deficit irrigation strategies on yield, fruit quality and some parameters: "Braeburn" apple cultivar. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **41**, 510–517.

Küçükyumuk C, Yıldız H, Ertek A and Kukul Kurttaş YS (2014) Effects of Different Irrigation Programs and Soil Water Variations on Leaf Water Potential of Apple. II. International Drought and Desertification Symposium, 16–18 September 2014, Konya, Proceedings Book, pp. 510–515.

Küçükyumuk C, Yıldız H, Sarısu HC, Kaçal E and Koçal H (2015) Response of sweet cherry grafted on different rootstocks to water stress. *Fresenius Environmental Bulletin* **24**, 3014–3024.

Livellara N, Saavedra F and Salgado E (2011) Plant based indicators for irrigation scheduling in young cherry trees. *Agricultural Water Management* **98**, 684–690.

Lo Bianco R, Talluto G and Farina V (2012) Effects of partial root zone drying and rootstock vigour on dry matter partitioning of apple trees (*Malus domestica* c.var Pink Lady). *Journal of Agricultural Science Cambridge* **150**, 75–86.

Mali SS (2016) Approaches to Improve Agricultural Water Productivity. Edition: 2016. Chapter: 1. Publisher: Satish Serial Publishing House. Editors: A K Singh, Santosh S Mali, Bikash Das, P Bhavana, PR Kumar, Bikash Sarkar, B P Bhatt. Pp: 1–13, SN: 9789385055805.

Marsal J, López G, Arbones A, Mata M, Vallverdu X and Girona J (2009) Influence of postharvest deficit irrigation and pre-harvest fruit thinning on sweet cherry (cv. New Star) fruit firmness and quality. *The Journal of Horticultural Science and Biotechnology* **84**, 273–278.

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

Mert C and Soylu A (2007) Possible cause of low fruit set in the sweet cherry cultivar 0900 Ziraat. *Canadian Journal of Plant Science* **87**, 593–594.

Monino MJ, Blanco-Cipollone F, Vivas A, Bodelon OG and Prieto MH (2020) Evaluation of different deficit irrigation strategies in the late-maturing Japanese plum cultivar "Angeleno". *Agricultural Water Management* **234**, 106111.

Mpelasoka BS, Behboudian MH and Green SR (2001) Water use, yield and fruit quality of lysimeter-grown apple trees: responses to deficit irrigation and to crop load. *Irrigation Science* **20**, 107–113.

Neilsen GH, Neilsen D, Kappel F and 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**, 215–220.

Nieto E, Prieto MH, Fortes R, Gonzalez V and Campillo C (2017) Response of a long-lived cherry cultivar to contrasting irrigation strategies in the Jerte Valley, Extremadura, Spain. *Acta Horticulturae* **1161**, 197–204.

Ortega-Farias S, Villalobos-Soublett E, Riveros-Burgos C, Zúniga M and Ahumada-Orellana LE (2020) Effect of irrigation cut-off strategies on yield, water productivity and gas exchange in a drip-irrigated hazelnut (Corylus avellana L. cv. Tonda di Giffoni) orchard under semiarid conditions. *Agricultural Water Management* **238**, 106173.

Pérez-Pastor A, Domingo R, Torrecillas A and Ruiz-Sánchez MC (2009) Response of apricot trees to deficit irrigation strategies. *Irrigation Science* **27**, 231–242.

Rieger M and Duemmel MJ (1992) Comparison of drought resistance among Prunus species from divergent habitats. *Tree Physiology* **11**, 369–380.

Ruiz-Sanchez MC, Domingo R and Castel JR (2010) Review. Deficit irrigation in fruit trees and vines in Spain. *Spanish Journal of Agricultural Research* **8**, 5.

SAS Institute (2002) *JMP Statistics*. Cary, NC, USA: SAS Institute, Inc, p. 707.

Shackel KA, Ahmadi H, Biasi W, Buchner W, Goldhamer D, Gurusinghe S, Hasey J, Kester D, Krueger B, Lampinen B, McGourty G, Micke W, Mitcham E, Olson B, Pelletraou K, Philips H, Ramos D, Shwankl L, Sibett S, Snyder R, Southwick S, Stevenson M, Thorpe N, Weinbaum S and Yeager J (1997) Plant water status as an index of irrigation need in deciduous fruit trees. *HortTechnology* **7**, 23–29.

Taiz L and Zeiger E (1998) *Plant Physiology*, 2nd Edn. Sunderland, Massachusetts: Sinauer Associates Inc, 792 pp.

Talluto G, Farina V, Volpe G and Lo Bianco R (2008) Effects of partial root zone drying and rootstock vigour on growth and fruit quality of 'Pink Lady' apple trees in Mediterranean and environments. *Australian Journal of Agricultural Research* **59**, 785–794.

Torrecillas A, Domingo R, Galego R and Ruiz-Sánchez MC (2000) Apricot tree response to withholding irrigation at different phenological periods. *Scientia Horticulturae* **85**, 201–215.

Yazgan S, Büyükcangaz H, Demirtaş Ç and Candoğan BN (2006) Evapotranspiration for young sweet cherry trees (*Prunus avium*) and growth responses to irrigation. *Pakistan Journal of Biological Science* **9**, 39–44.

Yıldırım O (2005) *Irrigation Project Design*. Ankara University Agriculture Faculty Publishing: 1542, Lesson book: 495, Ankara:348 p.

Yıldız H, Küçükyumuk C, Sarısu HC, Öztürk FP, Üzümcü SS, Türkeli B, Seymen T, Cansu M and Gülcü M (2021) *The Effects of Regulated Deficit Irrigations on Yield, Fruit Quality and Storage of Sweet Cherry*. Project Report, General Directorate of Agricultural Researches and Policies, Project Number: TAGEM/TSKAD/15/A13/P02/14, 86 p., Eğirdir, Isparta, Turkey.