



Influence of the rehydration period on yield quality and harvest performance in Manzanilla de Sevilla super high-density olive orchards

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Received: 28 November 2023 / Accepted: 29 April 2024
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Abstract

Super-high density olive orchards may increase profitability for table olive producers. However, water needs and fruit damage could limit their viability. Deficit irrigation scheduling would reduce the amount of water required, but rehydration before harvest is extremely important. The aim of this work was to compare a typical deficit farm management model with a regulated deficit irrigation one based on the plant water status. The experiment was carried out during three seasons in a three years-old (4 × 1.5 m) commercial table olive orchard. In both irrigation scheduling plots, seasonal amount of applied water was similar. Irrigation treatments were: common farm management (CFM), an almost constant rate of irrigation, and Regulated deficit (RDI) based on midday shaded water potential. Vegetative measurements suggested that RDI increased the external surface of the hedge, and this was related with greater yield in this treatment. Significant differences were found in of fruit size at harvest in some seasons, with larger fruits in RDI compared to CFM. However, fruit damage occurred during mechanical harvest in both irrigation managements, despite the higher skin firmness in RDI, and shows the need to carry out postharvest treatments to improve the quality of the final product. Accurate control of the tree water status would allow optimizing the amount of water available for table olive orchards.

Introduction

The first commercial orchards for table olive production under super high-density conditions were planted at the end of the 2010's, with tree densities often higher than 1500 trees per hectare, similar to those for oil production, and grown under irrigation (Morales-Sillero et al. 2014, 2023; Pérez-Ruiz et al. 2018). These orchards, as the ones of oil cultivars, need a high initial investment to cover plant material and infrastructures. Nonetheless, higher yield productions are expected in the early years in comparison to less intensive orchards, and mechanical operations, in particular harvesting and pruning, usually reduce the costs for olive growers (Connor et al. 2014). The high density of trees arranged in rows helps the harvesting, using over-the-row harvesters that collect most of the production in less than two to three hours

per hectare, which makes harvesting highly efficient (Connor et al. 2014; Pérez-Ruiz et al. 2018).

Regardless of the density of trees in a commercial orchard, the table olive industry usually requires fruits with weights that vary from 3 to 5 g, high pulp-to-pit ratio (> 5), homogenous distribution of commercial sizes (number of fruits per kilogram), and absence of damage, among other traits (Rallo et al. 2018). Taking into account the latter, over-the-row harvesters could limit the viability of super-high-density orchards for table uses. Previous works highlighted the damage caused by the harvester to the fruit, probably due to the contact with the rods that radiate from a vertical cylinder, extend into the canopy, and rotate to shake shoots and small branches (Connor et al. 2014; Pérez-Ruiz et al. 2018). After fruit removal, physiological changes are induced in the fruit (Morales-Sillero et al. 2023) and external damage (usually called bruising) can be noticed after a few minutes. Internal dark spots and tissue ruptures, both in the skin and the pulp, have also been reported (Jiménez et al. 2017; Morales-Sillero et al. 2023). The immersion of fruits in a cold diluted solution of

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NaOH just after harvest drastically decreases the damage (Rejano et al. 2008; Zipori et al. 2021).

The water needs of super-high density olive orchards could also affect the viability of this system for table olive production because the applied water in these orchards is higher in some locations than in less dense traditional management ones (Pastor et al. 2007). This is one of the most important disadvantages of this system in oil and table olive production. Although deficit irrigation may reduce water needs significantly in comparison to the data shown by Pastor et al. (2007), such reduction is limited in table olive orchards. Regulated deficit irrigation in these orchards, as in oil cultivars, is recommended during pit hardening (Goldhamer 1999). However, in table olive production, the rehydration before harvest is very important and affects the final fruit size in deficits treatments (Girón et al. 2015a; Corell et al. 2020). This rehydration could be affected by the fruit load that increase crop evapotranspiration (Bustan et al. 2016). Corell et al. (2020) reported a relationship between fruit size and yield, and concluded that, under conditions of high yield (above 10 t ha^{-1}), where fruit size will be small, the viability of deficit irrigation was reduced. Only when yield was lower than 10 t ha^{-1} , irrigation management could be optimized to reduce the effect on fruit quality (Corell et al. 2020), provided rehydration lasted long enough (Girón et al. 2015a; Corell et al. 2020). On the other hand, this period of water stress could improve some fruit features in relation to mechanical harvest. Casanova et al. (2017) reported that the most severe water stress conditions in this period reduced the size of fruit bruises in comparison to full irrigated or moderate water stress. These results suggested that a controlled level of water stress during pit hardening, with an adequate rehydration, could lower the water needs and improve fruit quality in super-high density olive orchards.

Water availability in commercial orchards is typically lower than the water needs. Therefore, growers must apply a deficit irrigation that could be present even in the rehydration period. This occurs because irrigation scheduling is usually fixed every season, or when the tree water status is not considered. Ben-Gal et al. (2021) reported that irrigation management based on water status measurements optimizes the water deficit applied in oil orchards. The aim of this work was to study the response of yield quality and quantity to deficit irrigation, and the harvest performance in super high density 'Manzanilla de Sevilla' olive orchards, a traditional cultivar which fruits are today highly appreciated by consumers worldwide (Zipori et al. 2021). The hypothesis of the work was that regulated deficit irrigation based on water status measurements could improve fruit quality and yield performance in comparison to a typical farm management.

Material and methods

Orchard features and experimental design

A three-year study was initiated in 2018, in a drip irrigated commercial olive orchard (cv Manzanilla de Sevilla) located in Morón de la Frontera (37.1° N , 5.5° W , 297 mas, Seville, Spain), with trees placed in a $4.5 \times 1.5 \text{ m}$ layout and a North–South orientation. The orchard was three years old at the beginning of the experiment. The climate of the area was Mediterranean, with warm winters and very dry summers (Fig. 1). The annual precipitation was 722 mm in 2018, 345 mm in 2019, and 415 mm in 2020. The reference evapotranspiration (ET_o) was 1202 mm, 1335 mm, and 1323 mm, respectively. The average annual temperature was around 18° C and ranged between 37° C in August and 4° C in January or February, depending on the year. The soil is a red vertisol, very hard when dry, and extremely plastic when wet. The useful depth is of approximately 1 m, with a clayey texture in the first 0.4 m and clayey-silty below that. It is an alkaline soil ($\text{pH} \approx 7.6$), not saline (electrical conductivity $\leq 0.110 \text{ dS/m}$), with high Cation Exchange Capacity (29.5 meq/100 g) and a carbonate content that ranges between 0.7 and 22.6% CaCO_3 .

The hedges were always pruned in February. The height was capped to around 2.3 m using a disc pruner. The width of the row was limited to 1 m in 2018 and 1.4 m in 2019 and 2020, by eliminating the thickest or badly positioned branches. In 2019, a lateral pruning was done first with the disc pruner. The nutritional needs were met through fertigation supported by a foliar analysis carried out in July. All treatments received similar amount of nutrients and no significant differences were found in foliar analysis (data not shown). Regarding soil management, a natural plant cover was maintained between rows and mowed in spring. Weed control in the tree lines was done by spraying herbicides.

The water was applied using a localized irrigation system with an integrated line of drippers and a flow rate of 2.3 L/h, placed 0.75 m apart. Water source was groundwater and it had an alkaline pH (7.6), a moderate electrical conductivity (1.07 dS/m), and high alkaline (234 ppm), calcium (151 ppm) and nitrate content (115 ppm). The experimental design consisted of completed randomized plots with two irrigation treatments and four repetitions per treatment. Each plot had a central row, where measurements were obtained, and it was flanked by two guard rows. Two irrigation treatments were applied:

- Common Farm Management (CFM). This management was decided by the owner of the orchard. Irrigation scheduling consisted of almost constant rate of irri-

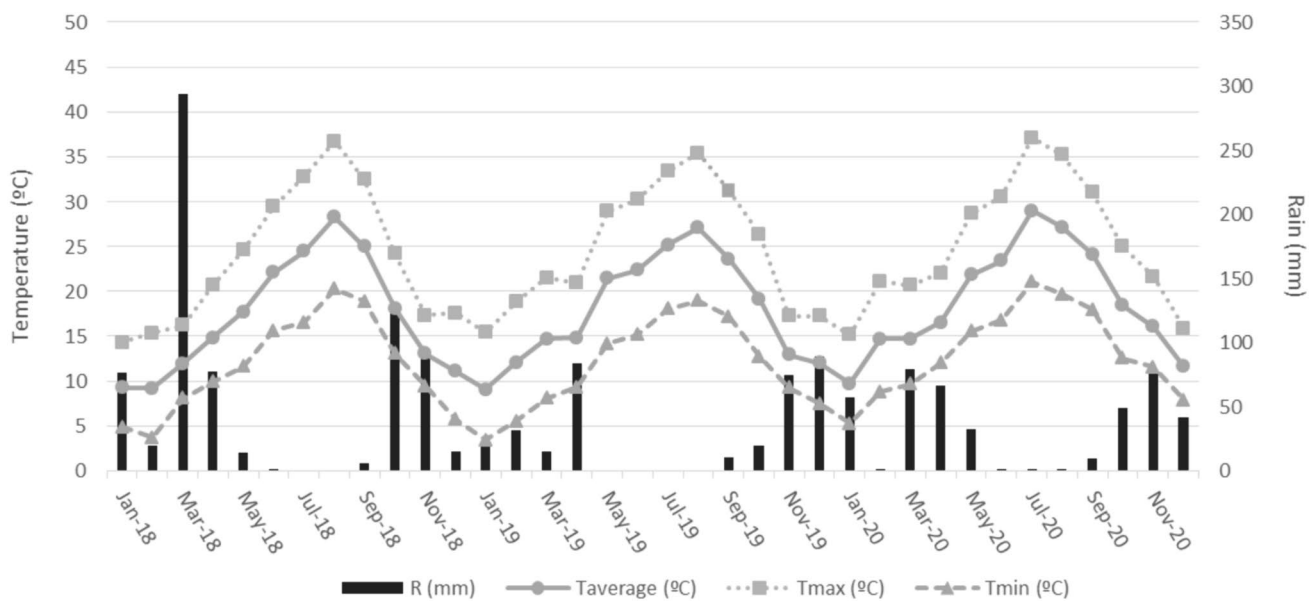


Fig. 1 Monthly rainfall and mean temperature of 2018, 2019 and 2020 in the experimental farm

gation throughout the season (Fig. 2). No differences between phenological stages were found, and differences between years were related to the fruit load (in 2019, fruit load was very small) and rainfall distribution.

- Regulated deficit irrigation (RDI). Irrigation scheduling was based on water status measurements and considered the phenological stage of the trees. The water stress level was characterized using midday shaded water potential (SWP) measurements. The irrigation season was divided in three different phases (Table 1), according to Moriana et al. (2012):
 - o Phase I. From shoot sprouting until the beginning of pit hardening (DOY 197 in 2018, DOY 170 in 2019, and DOY 174 in 2020). The most sensitive phenological stages occurred during this period (vegetative growth, flowering, and fruit set). Therefore, full irrigation conditions were provided and SWP was around -1.2 MPa (Moriana et al. 2012).
 - o Phase II. From the beginning of pit hardening until the third week of August (DOY 246 in 2018, DOY 238 in 2019, DOY 230 in 2020). This is considered the less sensitive part of the season. The beginning of pit hardening was estimated according to Rapoport et al. (2013). In short, longitudinal fruit length was measured with an electronical caliper in ten fruits per repetition. Statistical analysis was performed with the average of these measurements per repetition. Then, pit hardening started when the increase in fruit length decreased. Because pit hardness was not measured, the end of this period was estimated with a fix date, which was commonly recommended for RDI (Girón et al. 2015a; Corell et al. 2020). The level of SWP considered was -3.0 MPa, which minimized the risk of fruit drop according to several authors (Girón et al. 2015a; Corell et al. 2020).
 - o Phase III. From the third week of August until harvest. Partial recovery was performed during this period. The target value of SWP was -2.0 MPa, which would allow the fruit size to recover, according to several authors (Girón et al. 2015a; Corell et al. 2020; Martín-Palomo et al. 2020).

The irrigation scheduling in the RDI treatment was adjusted to the target values of SWP in each period. Irrigation was increased from 1 mm day^{-1} to 4 mm day^{-1} according to the weekly measurements of SWP in each plot of RDI treatment. The increase was similar to the ones suggested by Moriana et al. (2012) and ranged based on the distance from the SWP measurement to the target value of SWP. Each repetition of this treatment was scheduling individually every week. Then, all repetitions were not irrigated at the same time, mainly during pit hardening period.

These irrigation managements required the amount of applied water presented in Fig. 2. CFM treatment received an almost constant rate of irrigation throughout the season, while the RDI treatment changed according to SWP measurements. RDI commonly obtained a reduced irrigation during the pit hardening period, then it increased again during rehydration. In the first season (Fig. 2a), the main differences

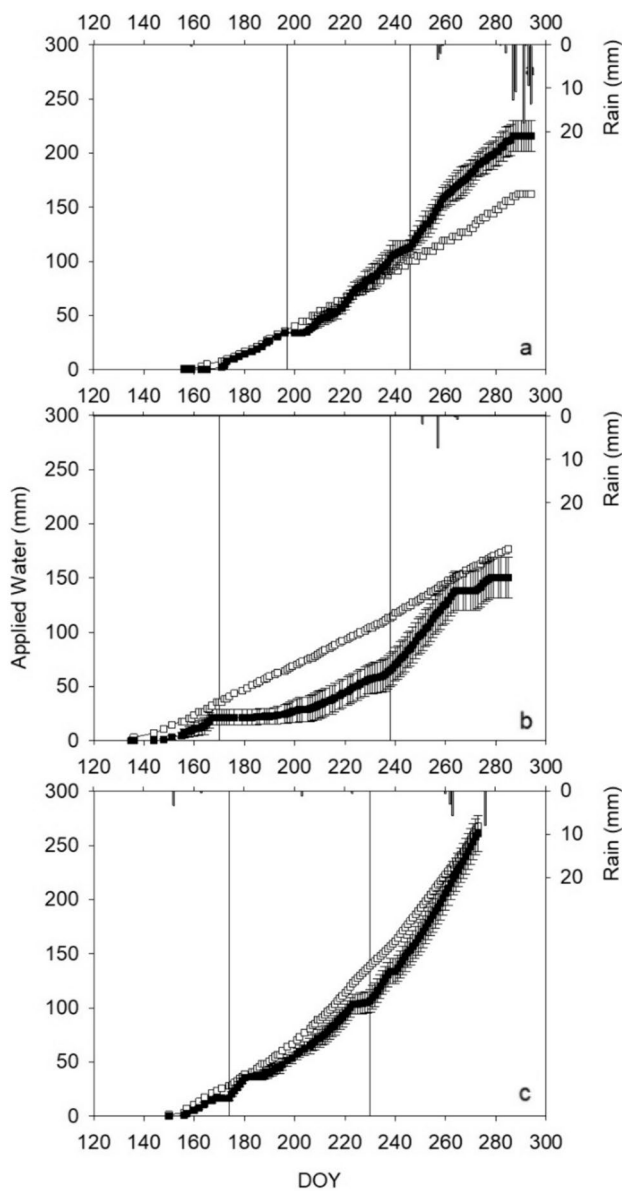


Fig. 2 Applied water along the three years of the experiment **a** 2018, **b** 2019 and **c** 2020. White squares, CFM applied water; black square, RDI treatment. Each point in RDI treatment was the average of four values. Vertical bars are standard error. Vertical lines limit the phenological Phase II (pit hardening)

Table 1 Dates, as days after full bloom, of the different phenological stages in the three seasons of the experiment

Season	Full bloom	Pit hardening	Recovery
2018	135	62	111
2019	115	55	123
2020	108	66	122

Only the date of full bloom is presented as day of the year (DOY)

in applied water occurred during rehydration. At the beginning of pit hardening, irrigation was slightly reduced in RDI in comparison to CFM, although it increased again towards the middle of the period. The seasonal amount of water applied in RDI reached values slightly below 250 mm, while CFM was around 160 mm (Fig. 2a). In the rehydration period, RDI used 103 mm, but CFM only applied 62 mm. In 2019 (Fig. 2b), the lowest fruit load season, both treatments required the same seasonal amount of water (around 150 mm) but with a very different seasonal pattern.

In RDI, water was saved during pit hardening (70 mm in RDI vs 117 mm in CFM) and used during rehydration, which was clearly greater in RDI than CFM (Fig. 2b). In the latter season (Fig. 2c), the total amount of applied water was at its maximum for both treatments, reaching around 265 mm. The rainfall scarcity was responsible for this high increase in both treatments. Differences in applied water between them was at its lowest, but, at pit hardening, RDI applied 104 mm while CFM increased to 138 mm. During rehydration, the pattern was the opposite, RDI consumed 157 mm but CFM received 129 mm until the end of the experiment.

Water status measurements

SWP measurements were taken using the pressure bomb technique (model 600, PMS, USA) in full expanded healthy leaves, which were grown in the interior of the canopy and received minimum radiation. Although this is not the approach for stem water potential measurement, the comparison between both (shaded and stem) was very similar (A Moriana unpublished data, Shaded = 1.06*Stem; $n = 165$; $R^2 = 0.83$). These data were used for estimating the stress integral (SI) and to include the effect of the water stress duration. The SI was calculated according to a modified version of the Myers formula (Myers 1988). Myers (1988) suggested the estimation of SI using the maximum value obtained in the season. However, this value changed and could not be a reference for water stress. Consequently, the maximum value was estimated on each measured date as the one obtained using the baseline of Corell et al. (2016).

$$SI = |(SWP - LB) * n|, \quad (1)$$

where:SI, stress integral (MPa*day).SWP, midday shaded water (MPa).LB, water potential value obtained in the baseline equation.N, number of days.

Hedgerow characteristics

In each experimental unit, ten trees were randomly selected in April 2018 (before the beginning of the study) to determine the canopy height, the perimeter of the trunk at 0.3 m,

and the mean width from measurements at 0.8 and 1.7 m of height. From the height and width measurements, the average External Foliar Surface (EFS, $\text{m}^2 \text{ha}^{-1}$) was determined considering a rectangular prism shape in the hedge. All these measurements were also made in December of each experimental year. Besides, hedgerow porosity was estimated by image analysis of digital pictures that were taken with a Nikon D600 reflex camera (Nikon Corp., Tokyo, Japan) with a red sheet previously placed in the background of the hedgerow. A CobCal software ver. 2.0 (Bs As, Argentina) was used to process the images digitally and to estimate the average percentage of gaps by dividing the number of red pixels (i.e., background sheet) by the total number of red and green pixels (i.e., leaves and stems).

Fruit quality, fruit yield and removal efficiency

Fruits were harvested mechanically on 25 October (DOY 298) in 2018, 17 September (DOY 260) in 2019, and 30 September (DOY 273) in 2020. At first, the harvest was planned to be carried out once the fruits had yellowish-green epidermis and the pulp was easily separated from the stone. However, in 2018 it was delayed due to the rainfall occurred (≈ 65 mm) two weeks before achieving this maturity index (Fig. 1). Previously, samples of three kilograms of olives per each experimental unit were taken for fruit trait measurement. Thus, the unitary and the average fruit weight (g) were obtained from a subsample of 100 fruits, and the size distribution (fruit count per kg) was established according to the US Standards for Green olive size designations (USDA 2019), that consider the following categories: Extra-large (< 200), Large (220–240), Medium and Small (241–300), Petite (301–400), Subpetite (401–420) and smaller than subpetite (> 420). The pulp-to-pit ratio was estimated using a 0.5 kg subsample based on the difference between the weights of fruit and pits. The average fruit volume (mL) was determined by immersion of 100 fruits in a 1 L graduated cylinder filled with 500 mL of water. Fruit shape is the ratio between the maximum longitudinal and equatorial diameters (mm), that were measured in 50 fruits with a digital caliper. The L^* , a^* and b^* skin color parameters were measured on the equatorial zone of 30 fruits with a Minolta CM-700d (Konica Minolta Inc., Tokyo, Japan) spectrophotometer, and the color index was estimated as indicated in Castellano et al. (1993). The moisture and oil contents (%) were estimated using 10 g of crushed olives after oven-drying at 100°C for 24 h until reaching a constant weight. The oil content was measured in the dry samples by nuclear magnetic resonance on a Maran Ultra spectrometer (Oxford Instruments, UK). To evaluate the fruit size according to irrigation management the relation between yield and average number of fruits per kilogram in each repetition were obtained. These values were compared with the ones reported in Corell et al.

(2020) for different irrigation strategies and then evaluated the potential fruit size reduction expected according to yield.

Mechanical harvesting was done at dawn with a New Holland VX 7090 combine (CNH Global, Belgium) at a speed of 1.5 km h^{-1} and a 60% header opening in 2018 and 2019, and 2 km h^{-1} and 90%, respectively in 2020, all years with a frequency of 430 beats/min. Later, fruit yield (kg ha^{-1}) was estimated for each experimental unit from the total production removed by the harvester and the number of trees, the weight of the fruits left in 10 randomly selected trees (fruits were hand-picked from 0.6 m above the ground), and the weight of fallen fruits to the ground collected in a 4.5×2.5 m net placed on each side of the hedge. The removal efficiency was established as the percentage of fruits that were collected by the harvester. The number of fruits per external surface area (Number fruit m^{-2}) was estimated from the number of fruits per kilogram, number of fruits per hectare and EFS data ($\text{m}^2 \text{ha}^{-1}$).

Mechanical properties of fruits and fruit damage after mechanical harvesting

Samples of three kilograms of olives per each experimental unit were also taken immediately after mechanical harvesting for texture and damage measurements. Fruit firmness, hardness, and texture were assessed using a TA.XT.plus texture analyzer (Stable Micro Systems Ltd) connected to the Texture Exponent software (version 6.1.15.0). Three types of tests were respectively conducted: (a) puncture (N/mm), with a probe of a 2 mm diameter steel punch that penetrated up to 4 mm into the fruit at a constant speed of 0.50 mm/s ; (b) compression (N), with a 20 mm diameter TPA (Texture Profile Analysis) probe used at a speed of 1 mm/s , a deformation time of 2 s, and a deformability of 15%; and (c) shear compression force (N/g) by means of a Kramer cell (HDP/KS10 Cell), with 10 blades of 3 mm thickness each at a return speed of 10 mm/s . For each experimental unit, the measurements were made on the equatorial zone of 10 pitted fruits in the puncture test, 10 intact fruits in the compression test, and in 10 batches of three pitted fruits of similar weight in the compression-shear test.

Bruising damage was estimated from the percentage of fruits with cuts, bruising incidence, and the area and volume of the largest bruise. The percentage of fruit with cuts was measured 2 h after harvesting in a 100-fruit subsample for each experimental unit. In the same subsample, the bruising incidence was determined after classifying the fruits into three categories: non-bruised fruits, fruits with low damage ($< 25\%$ of the surface), and fruits with severe damage ($\geq 25\%$), according to Morales-Sillero et al. (2014). For the external bruised area (BA, mm^2) and bruising volume (BV, mm^3), 30 fruits were fixed two hours after harvest in formalin acetic acid [95% ethanol and distilled water (10:5:50:35

$v/v/v/v$]. An impact located in the equatorial zone of each fruit was chosen and the length, width, and damage depth were measured, assuming an elliptical shape in the damaged zone as indicated by Morales-Sillero et al. (2014).

Statistical analysis

The data obtained were statistically analyzed using the Stat-Graphics Centurion XVIII (Statpoint Technologies, The Plains, Virginia) software package, evaluating the effect of each treatment using an analysis of variance (ANOVA). The arcsine of the square root or Box-Cox power transformations (Box and Cox 1964) were used when necessary to achieve normality and homogenize the variance.

Results

The seasonal pattern of SWP was similar in the three seasons, with a decrease during pit hardening and a recovery before harvest (Fig. 3). In some dates, SWP values IN RDI trees were slightly different of the threshold consider in each phase. This was produced because each repetition was scheduling individually and irrigated only when they reached threshold values. Extreme values of SWP were different on different years. Values during Phase I, before pit hardening, were not significant in any of the seasons, although RDI tended to more positive values than CFM. In 2018, major differences in SWP were found from the beginning of Phase II (Fig. 3a). Before pit hardening, SWP values were very similar and close to the Corell's baseline. In Phase II, the distance to the baseline increased in both treatments (more than 1.5 MPa), and minimum values of SWP were reached (around -3 MPa). From this period onwards, CFM presented more negative values than RDI, although both increased during rehydration. In this season, rehydration was not completed in any of the treatments according to the baseline, but RDI presented more positive SWP than CFM. Only at the end of the recovery period, when rains started, rehydration was almost completed and SWP values were almost equal for both treatments. In the 2019 season (Fig. 3b), the SWP values were less negative than in the previous season for both treatments (minimum values around -2.5 MPa). Only at the beginning of Phase II and rehydration, RDI presented significantly better water status than CFM on a few dates. In this season, the recovery of both treatments was the best of the three years, with SWP values near the baseline. Finally, in the 2020 season (Fig. 3c), only significant differences in the rehydration period were found. Minimum SWP values in Phase II were around -3 MPa, as in 2018, but the recovery period was worse than in previous seasons. Partial rehydration was measured in that period, and it turned out to

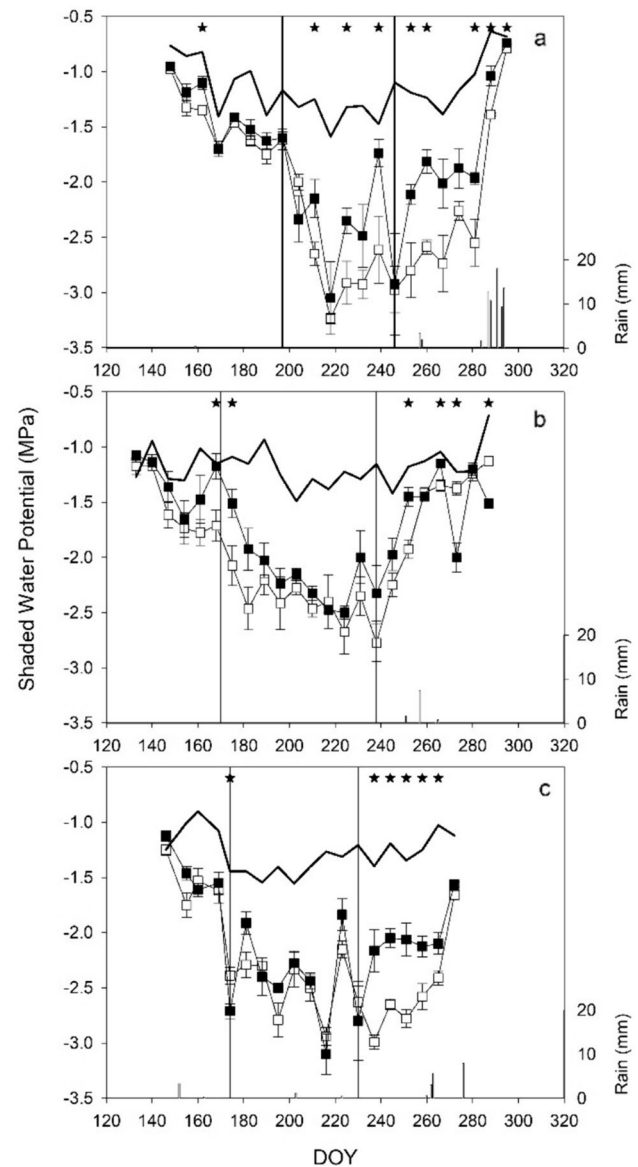


Fig. 3 Seasonal pattern of midday shaded water potential along the three season of the experiment **a** 2018, **b** 2019, **c** 2020. White square, CFM, black square, RDI. Each point is the average of four values. Vertical bars represent standard error. Vertical lines limit the phenological Phase II (pit hardening). Asterisks indicate significant differences at that date ($p < 0.05$, ANOVA). Solid line represents the values obtained in the baseline equation of Corell et al. (2016)

be better in RDI than in CFM. The latter increase of SWP was due to rains (≈ 10 mm) but SWP values were still more negative than the baseline.

Values of SI are presented in Fig. 4 and integrate the level and duration of the water stress. The peak SI for a whole season was measured in 2018, while the lowest was reported in 2019. Although only considerable differences were found in 2018 (Fig. 4a), the SI for the whole season was always greater in CFM than in the RDI treatment.

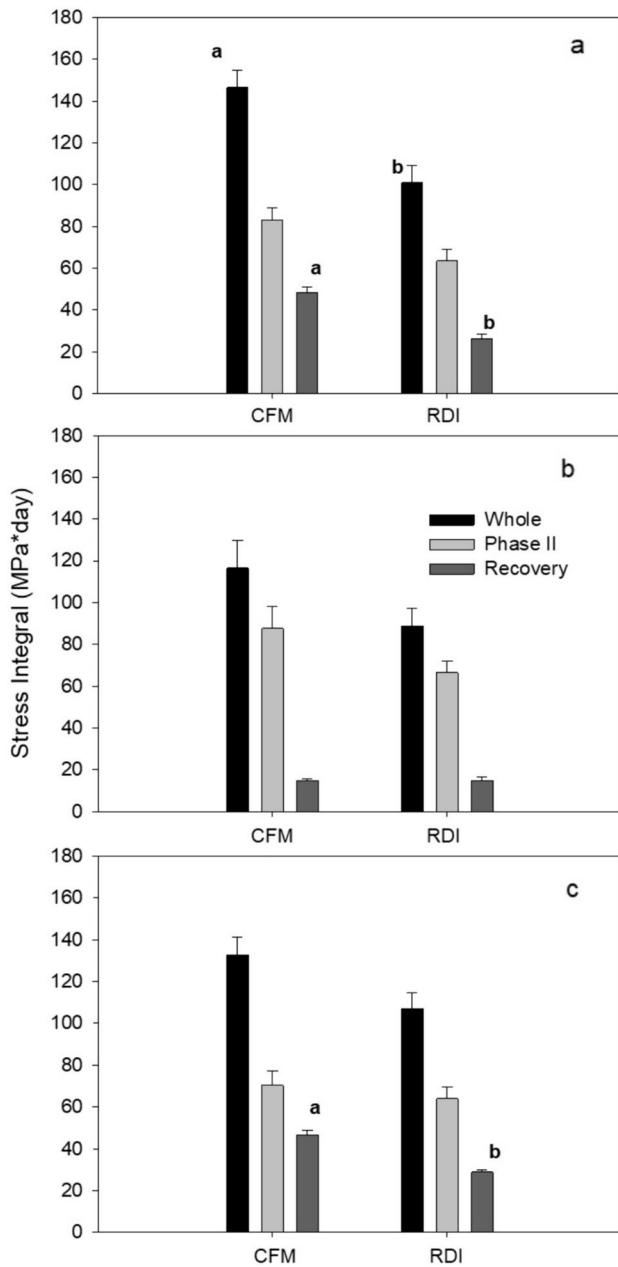


Fig. 4 Stress integral during **a** 2018, **b** 2019, **c** 2020 in three different periods of the season. Black, whole season; light grey, Phase II (pit hardening); black grey, rehydration. Each point is the average of four values. Vertical bars represent standard error. Different letters indicate significant differences between treatments for the same period each year ($p < 0.05$, ANOVA)

In all three years, the SI during Phase II was the highest when considering the whole season (more than 50%) but no significant differences were found between treatments in this period. However, the SI in CFM trees tended to greater values than in RDI ones in Phase II. The SI during the recovery period was significantly higher in CFM than in RDI in the 2018 and 2020 seasons (Fig. 4a, c). During rehydration,

the CFM SI was greater than 40 MPa*day and RDI values were around 25 MPa*day for both seasons. Conversely, the SI showed minimum values during recovery in 2019 and almost equal results for both treatments (Fig. 4b).

Significant differences were found in the hedgerow features throughout the three seasons (Table 2). For most of the measured indicators, RDI hedgerow presented a greater vegetative growth than CFM. Trunk perimeter increased in both treatments during the experiment, but it was only significantly greater in RDI than in CFM in December 2018. However, differences between RDI and CFM became greater from this date onwards and reached maximum values, around 3.4 mm of trunk perimeter, in December 2020. Hedgerow was always considerably higher in RDI than in CFM, but this was not the case with the width. Nevertheless, the external surface was also remarkably greater in RDI than in CFM, and the differences between treatments ranged from 3 to 7%, with maximum values in 2018. The porosity of the hedgerow changed in different years. The lowest value was estimated in December 2019, and the greatest in 2020. The porosity in CFM trees was higher than in RDI, although this difference was only significant in 2018.

The average values of different fruit traits are shown in Table 3. The Maturity Index was similar in the two treatments and close to 1 in 2019 and 2020, indicating that the harvest took place at the same state of maturity. However, in 2018, the mean values were equal or greater than 2, and maturation was significantly advanced in RDI fruits (maturity index 2.8). The mean values of fruit weight, volume, and pulp -to-pit ratio were also greater in 2018 (4.5, 4.7, and 9.9, respectively) and 2019 (4.5, 4.6, and 8.4, respectively) versus those in 2020 (3.5, 3.6, and 8.2, respectively), as well as in the RDI treatment versus the CFM treatment, although the differences between treatments were only significant in 2018. The shape index was approximately 1.2, meaning that the fruits were spherical, particularly the RDI ones, which showed the lowest values in 2018 and 2019 (Table 3). Fruits were slightly asymmetrical in 2018 and 2020 (2.1 mean values of fruit symmetry) and symmetrical in 2019 (1.1). Only in 2018, the differences between treatments were significant, the fruits of RDI being more symmetrical than those of CFM. Mean values of color traits (L^* , a^* , b^* and color index) were lower in RDI fruits than in the CFM ones, which means that the RDI fruits had lower lightness as well as lower green and yellow tones. Pronounced differences between treatments were found in 2018. Regarding chemical composition, the average percentage of water was of 66.2 in 2018, 60.5 in 2019 and 64.8 in 2020. RDI fruits always showed the highest water content (around 8, 9 and 3%, respectively). Conversely, the oil content was lower in this treatment compared to CFM, although the differences between both treatments were not significant in the last year of the study.

Table 2 Hedgerow vegetative structure and trunk perimeter throughout the experiment

	Apr-18		Dec-18		Dec-19		Dec-20	
	CFM	RDI	CFM	RDI	CFM	RDI	CFM	RDI
Height (m)	2.3	2.4	2.6a	2.8b	2.6a	2.7b	3.2a	3.3b
Width (m)	1	1.0	1.7	1.8	1.7	1.7	1.8	1.9
Trunk perimeter (mm)	48	47.6	55.1a	57.6b	71.5	74.5	86.1	89.5
External surface area (m ² ha ⁻¹)	11751.1	12196.8	16239.2a	17448.8b	17167.5a	17720.7b	20370.3a	21070.8b
Porosity (%)			30.2b	24.7a	20.4	18.3	33.5	27.6

Lowercase letters indicate significant differences in irrigation treatments (ANOVA $P < 0.05$)

An absence of letters indicates a non-significant effect

Table 3 Fruit quality and yield components and percentage of fruit removal after mechanical harvesting in the three seasons of the experiment

	2018		2019		2020	
	CFM	RDI	CFM	RDI	CFM	RDI
Maturity index	2.0a	2.8b	1.4	1.3	1.1	1.1
Fruit weight (g)	4.1a	4.8b	4.2	4.7	3.5	3.5
Fruit volume (mL)	4.2a	5.1b	4.3	4.8	3.6	3.6
Pulp-to-pit ratio	8.9a	10.8b	8.2	8.6	8.0	8.3
Shape index	1.2b	1.1a	1.2b	1.1a	1.2	1.2
Fruit symmetry	2.3b	1.9a	1.1	1.0	2.1	2.0
L*	59.5b	49.7a	58.3	56.2	61.9	61.1
a*	7.1a	0.1b	9.2	8.2	-10.2	-10.2
b*	39.2b	26.4a	40.7	37.5	43.0	42.1
Color index	28.9b	16.6a	29.5	26.9	33.2	32.0
Water content (%)	63.7a	68.7b	57.9a	63.0 b	63.9a	65.6b
Oil content (% d.w)	44.7b	41.2a	46.8b	43.9 a	40.0	39.0
Fruit yield (kg ha ⁻¹)	6630.0a	9290.0b	1610.0	1830.0	8530.0a	9230.0b
Number fruit m ⁻²	99.2a	110.2b	22.3	22.6	120.9	124.3
Fruit removal (%)	97.9	97.8	96.6	97.2	93.5	93.5

*L, Lightness; a, color axis from green to red; b, color axis from blue to yellow

Lowercase letters indicate significant differences in irrigation treatments (ANOVA $P < 0.05$)

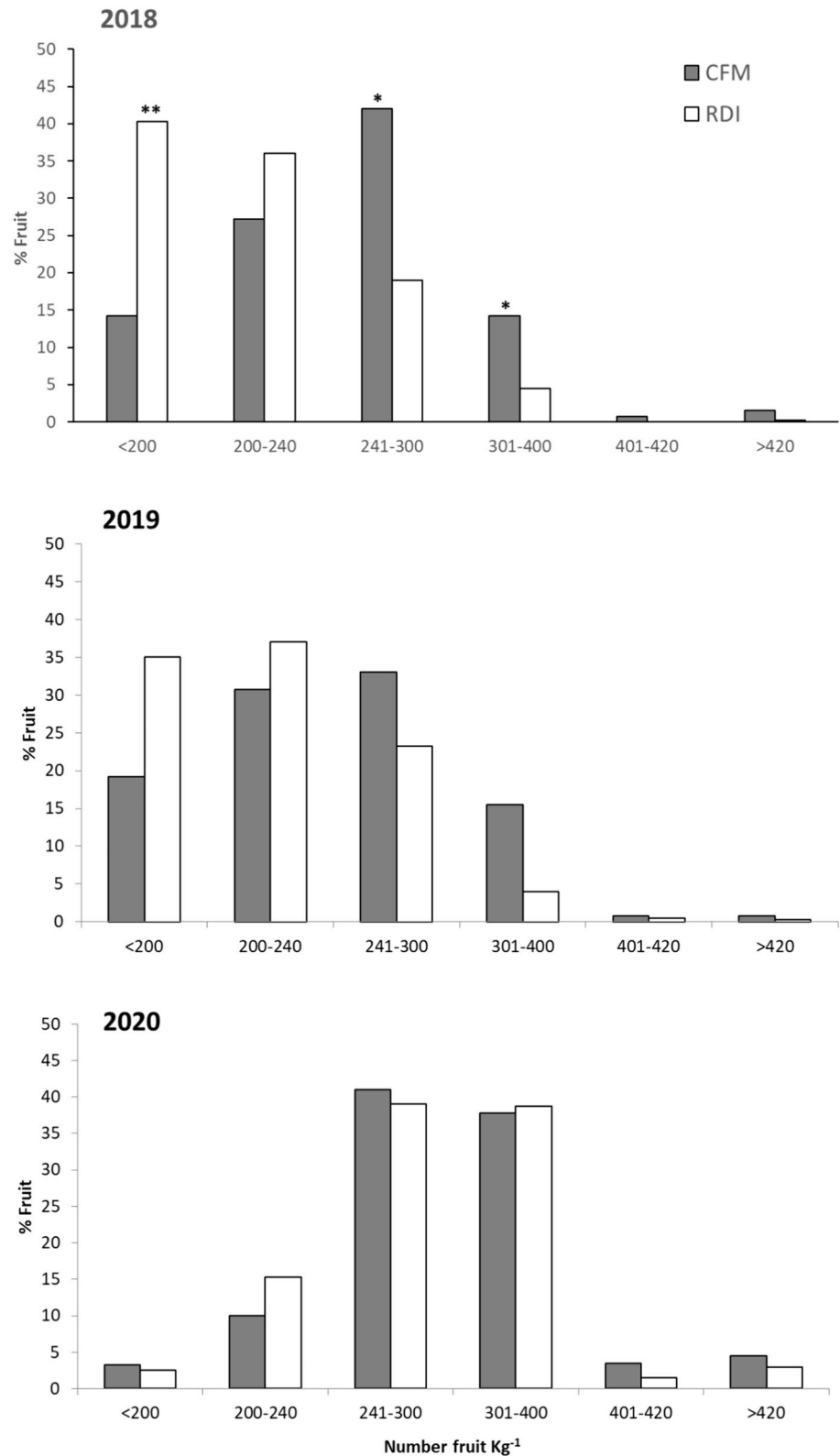
An absence of letters indicates a non-significant effect

The pattern of fruit size distribution and fruit length changed in the different seasons (Figs. 5, 6). Most fruits were distributed into the greatest size categories in the first two years. Remarkable differences between treatments were found only in 2018, when the larger fruits were found in RDI (Fig. 5). In this season, around 75% of the RDI fruits samples were classified as lower than 240 fruits kg⁻¹ (Medium or better size classification), while in CFM this percentage was down to 40%. Besides, the percentage of samples with lower than 200 fruits kg⁻¹ (Extra-large) were considerably higher in RDI than in CFM. Conversely, the percentage of the classes 241–300 (Medium and Small) and 301–400 (Petite) were greater in CFM. In 2019, fruit size distribution in the <200 (Extra-large) and 200–240 (Large) fruits kg⁻¹ increased in CFM and no significant differences were found between treatments (Fig. 5). The percentage of fruits in the class lower than 240 fruits kg⁻¹ was similar to the previous

season in RDI, around 70%, while in CFM it increased to 50%. The lowest fruit size in both treatments were harvested on the 2020 season (Fig. 5), when the percentage of samples lower than 240 fruits kg⁻¹ was slightly greater in RDI (20%) than in CFM (15%), but small in comparison to previous seasons. The most common samples in both treatments were in the classes 241–300 (Medium) and 301–400 (Small), which is around 70% of the total number of samples.

The pattern of fruit length (Fig. 6) was estimated along the season and the beginning of the pit hardening period was recorded according to Rapoport et al. (2013). Fruit length increased almost linearly during the first 40–60 days after full bloom when both treatments decreased the growth (Fig. 6). Only at 2018 season, RDI fruit length was significantly bigger at harvest (Fig. 6a). In the other two seasons, fruit length was almost equal all the time, only at harvest of 2019, RDI trended to higher value than CFM (Fig. 6a, b).

Fig. 5 Fruit size distribution (fruits kg^{-1}) by irrigation treatment. Asterisks indicate significant differences between treatments (Tukey Test, $p \leq 0.05$)



The average fruit yield was 7960 kg ha^{-1} in 2018, 1720 kg ha^{-1} in 2019, and 8880 kg ha^{-1} in 2020, and the RDI hedges showed the highest production, about 40, 14, and

8%, respectively, greater than in CFM hedges (Table 3). Both treatments presented an alternate bearing pattern with a strong decrease in 2019, in comparison to 2018 and 2020, which is

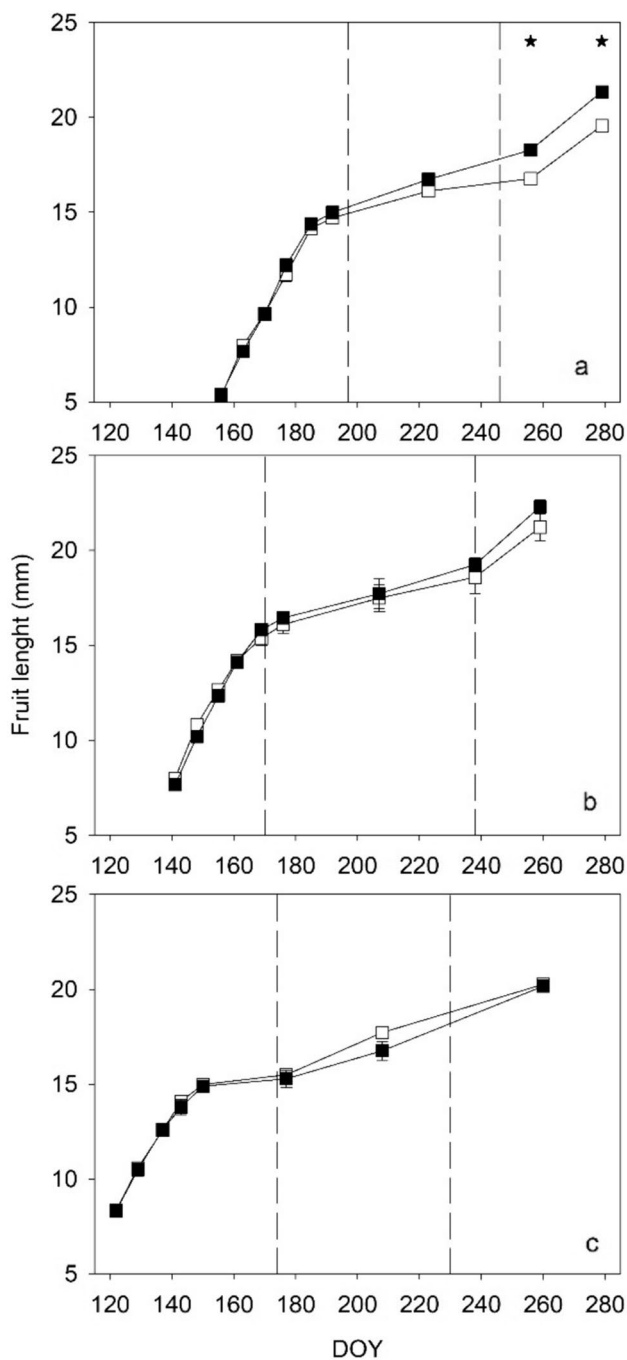


Fig. 6 Fruit length pattern along the 2018 (a), 2019 (b) and 2020 (c) seasons. White square, CFM, black square, RDI. Each point is the average of 4 data and vertical bars show the standard error. Vertical lines limit the phenological Phase II (pit hardening). Asterisks indicate significant differences at that date ($p < 0.05$, ANOVA)

common in this cultivar. Differences between treatments were relevant in 2018 and 2020. The number of fruits per external surface area was about 11 and 3% greater in the RDI hedges than in the CFM ones in 2018 and 2020, respectively, despite differences being remarkable only in 2018. No differences

were found between treatments in 2019 for this parameter. The real effect of irrigation treatments on yield and fruit size was difficult to evaluate because both measurements are linked in a way that the decrease in one, e.g., yield, would mean an increase in the other, e.g., fruit size. In order to be able to compare them accurately, the relationship between the yield and the average fruit size was obtained and contrasted with previously published data (Table 4 and Corell et al. 2020). The expected fruit size was estimated for four different irrigation managements (Corell et al. 2020). In all seasons, average fruit sizes were lower than expected for full irrigated conditions in both treatments; only RDI was greater in 2018 (Table 4). CFM average fruit sizes presented lower values than those for the highest stress management treatments of Corell et al. (2020), except in 2018, when values were close to those for moderate water stress conditions. On the contrary, RDI fruit sizes were better than the CFM ones, similar to the values expected under conditions of severe water stress in 2020, and better than full irrigated treatment in 2018 in Corell's relationships.

Removal efficiency after mechanical harvesting was 98% in 2018, 97% in 2019 and 94% in 2020, without major differences between treatments (Table 3). Mechanical properties and damage of the fruits after harvest are shown in Table 5. In the first season, no differences between treatments were found. The fruits showed 7.2 N of skin firmness, 43.8 N of hardness and 34.7 N g^{-1} of texture (mean values). They had no cuts but showed external and internal bruising damage. Bruising incidence was 1.5 in CFM fruits and 1.4 in RDI fruits, as this treatment had the lowest percentage of fruits with severe external damage (38.5%, in contrast to the 50% of CFM). The mean values of bruising area and volume were 26.7 mm^2 and 58.1 mm^3 , respectively. In 2019 and 2020, the values of hardness and texture of the fruits were similar between treatments and higher than those of 2018 (around 9 and 7%, respectively). However, for these years, RDI fruits had 9% firmer skin than CFM fruits, which is a significant difference between treatments. Despite this, bruising incidence increased to 1.7 in both due to the higher percentage of fruits with severe damage (> 66%). The percentage of fruits with cuts also increased compared to 2018, up to 15% in the CFM treatment and to a lesser extent in the RDI treatment (12.4% in 2019 and 10.5% in 2020), although no significant differences between them were found neither in the bruising area nor in the volume. Mean values of both traits were 30.8 mm^2 and 73.8 mm^3 respectively in 2019, and 27.2 mm^2 and 66.8 mm^3 in 2020.

Discussion

Yield response was likely more related with water status of the trees than with seasonal applied water data. Maximum yields around 9000 kg ha^{-1} were measured in RDI

Table 4 Comparison of average fruit size measured in the experiment and the values expected according to the yield of Table 3 (first two left columns)

	Yield ^a	Fruit size	Full	Low	Moderate	Severe
CFM 18	6630	243.9	222.2	225.1	243.5	253.9
RDI18	9290	208.3	240.2	248.1	275.3	285.7
CFM 19	1610	238.1	188.2	181.7	183.6	193.9
RDI 19	1830	212.8	189.7	183.6	186.3	196.5
CFM 20	8530	285.7	235.1	241.6	266.2	276.6
RDI 20	9230	285.7	239.8	247.6	274.5	285.0

Expected values were obtained from Corell et al. (2020) considering full irrigated, low, moderate, and severe water stress equations of this latter publication

^aYield (kg ha⁻¹), Fruit size (number kg⁻¹), Full, low, moderate, severe values are expected values obtained using the equations from Corell et al. (2020) named as Control, RDI-2, RDI-1, RDI-3 respectively in the work (number kg⁻¹)

Table 5 Mechanical properties of fruits and damage after mechanical harvesting

	2018		2019		2020	
	CFM	RDI	CFM	RDI	CFM	RDI
Skin firmness (N)	7.1	7.2	7.8a	8.5b	6.8a	7.4b
Hardness (N)	42.6	44.9	46.5	50.6	47.0	41.1
Texture (N g ⁻¹)	34.7	34.7	37.2	36.2	37.4	36.4
Bruised fruits (%)						
Low damage	50.0	61.5	26.3	30.1	33.8	31.5
Severe damage	50.0	38.5	73.8	69.9	66.2	68.5
Bruising incidence	1.5	1.4	1.7	1.7	1.7	1.7
Cut fruits (%)	0.0	0.0	14.5	12.4	15.4	10.5
Bruising area (mm ²)	25.6	27.7	30.3	31.3	26.7	27.7
Bruising volume (mm ³)	55.5	60.7	71.8	75.7	67.7	65.9

Lowercase letters indicate significant differences in irrigation treatments (ANOVA $P < 0.05$)

An absence of letters indicates a non-significant effect

during 2018 and 2020 seasons (Table 4) with applied water between 215 (2018) and 261 (2020) mm (Fig. 2). Differences between seasons were related with the rain scarcity in 2020 (Fig. 1). However, CFM treatment with similar applied water in 2020 (Fig. 2) presented lower yield than RDI (Table 4), though in the previous season was also very similar to RDI. Applied water was the common variable to define irrigation scheduling, although this is strongly influenced by water status in the same orchard, the environmental conditions, and therefore water stress, would be, in fact, the most important constraint. Ben-Gal et al. (2021) concluded that irrigation scheduling in olive trees would be more accurate when managed according to water status measurement. Although water needs would be very important to estimate irrigation, because of their relationship with fruit load (Bustan et al. 2016), the management of the moment and level of water stress will also be critical in the yield response (Hsiao 1990).

The main differences between treatment were obtained during the period of rehydration, although RDI presented a slightly better water status also in previous phenological stages (Figs. 3, 4). Such differences at the beginning of the experiment could enhance vegetative growth and increase

total yield (Tables 2, 3). Vegetative growth was reported as very sensitive to water stress, and it was affected earlier than the water potential (Hsiao 1990). Pierantozzi et al. (2020) reported that the decrease of crown volume reduced yield response in young olive orchards, and such result was similar to the one observed in the current work. Even though fruit yield increased in RDI, this strategy decreased oil percentage (Table 3). This response was likely related to the rehydration period. In the RDI strategy, the applied water was increased before harvest to ensure the recovery of fruit size (Goldhamer 1999; Girón et al. 2015a) and the most significant differences in water status were measured at this time-point. This increase of water stress could improve oil content in CFM in comparison to RDI. Several authors suggested that under conditions of moderate water stress, oil tended to increase as opposed to full irrigated trees (Grattan et al. 2006; Gucci et al. 2007; Lavee et al. 2007; Fernández et al. 2013; Ben-Gal et al. 2021). In addition, fruit load affected oil percentage with around 2 points higher in 2019 than in the other two seasons (Table 3). Several authors reported an increase of oil percentage in low fruit load seasons in all irrigation treatments (Naor et al. 2013; Ben-Gal et al. 2021, in

cv Askal but not in Barnea). Low fruit load seasons reduced transpiration (Bustan et al. 2016) and improved water status (Naor et al. 2013) as in the current work (Figs. 3, 4). These results suggest that the increase in oil percentage could be associated to seasonal water status as Corell et al. (2022) also reported, though the stress integral estimated in the current work would be lower than the ones reported as limiting in this latter work.

Table olive quality depends on many attributes, and the consumers usually demand medium to large fruits (> 3 g), with a high pulp-to-pit ratio ($\geq 5:1$), spherical rounded shape, and absence of damage (Rallo et al. 2018). Considering fruit size, results of the current work (Table 3, Fig. 5) showed that the fruits from irrigation strategies, RDI and CFM, could be commercialized by the industry. Besides, most fruits were distributed into commercial categories, which are based on the number of fruits per kilogram (USDA 2019; IOC 2004). The best distribution was observed in 2018 and 2019 (Fig. 5), which could be explained by rehydration driven by rain and irrigation (Figs. 1, 3), as well as the low fruit load in 2019 (Table 3). Conversely, the worst distribution of fruits into the different categories was found in 2020, as the recovery period during irrigation was not completed (Fig. 3). Besides, this season was drier than 2018 and just 249 mm were received before harvest (Fig. 1). RDI irrigation usually improved fruit size (Fig. 5, Table 3) and other fruit features, such as pulp to pit ratio (Table 3). Both features have been reported as strongly related to the period of rehydration, when RDI presented a better water status than CFM (Figs. 3, 4). Several authors reported that, after a short period of rehydration, even with stem water potential values similar to those under full irrigated conditions, fruit size and fruit pulp ratio slightly decreased (Girón et al. 2015a; Corell et al. 2020). However, the evaluation of the rehydration strategy was affected by changes in total yield. Changes in fruit size distribution and average fruit size in the different seasons were related to great variations in yield (Fig. 5, Table 3). In addition, because both treatments presented a water stress period during rehydration (Fig. 3), the actual effect of the water stress level was difficult to identify. The comparison with expected fruit size values (Table 4) suggested that both strategies in the current work limited fruit size in comparison to expected values in full irrigated conditions. However, these limitations were greater in CFM management, even though rehydration was almost completed in 2018 and 2019. Therefore, the rehydration strategy would have to be considered to minimize the stress integral in all rehydration periods, instead of decreasing the water potential a few weeks before harvest. The impact of cumulative water stress on fruit growth was suggested in Girón et al. (2015b) and, also in relation to oil yield, in Corell et al. (2022). However, minimum SI values were reported

in 2019 (Fig. 4), the lowest fruit load season, when fruit size was the worse in comparison to the Corell et al. 2020 estimation (Table 4). Under these conditions, the decrease of SWP below the baseline before the beginning of pit hardening (Fig. 3) could be responsible for the fruit size reduction at harvest. Several authors suggested that water stress in this period decreased the final fruit size, even when trees were under full irrigated conditions for the rest of the season (Gomez-del-campo et al. 2014; Gucci et al. 2019). However, the water stress level which produced this decrease in fruit size was more severe (-3 MPa predawn, Gucci et al. 2019) than the ones reported here (Fig. 3). Then, the reduction in fruit size in both treatments along the three seasons of the experiment could be more related with a partial and/or shorter period of rehydration than the ones reported in Corell et al. (2020).

In agreement with previous works (Morales-Sillero et al. 2014; Pérez-Ruiz et al. 2018), fruit removal with the over-the-row harvester was almost 100% and fruits showed a high level of damage (Table 5). In fact, Manzanilla de Sevilla fruit is considered highly susceptible to mechanical damage (Castro-García et al. 2015; Jiménez et al. 2017; Morales-Sillero et al. 2014; Zipori et al. 2014). Results of the current work highlight this issue, regardless the irrigation treatment, because the fruits showed similar external and internal damage, as demonstrated by the mean values of bruising incidence, area, and volume, as well as the proportions of fruit with cuts in 2019 and 2020 (Table 5). These results were observed despite the higher skin firmness of the RDI fruits, which was also evidenced in fruits from the same cultivar after a moderate water stress during the pit hardening period (Cano-Lamadrid et al. 2015). The quick immersion and the transportation of the fruits to the factory in diluted and cooled sodium hydroxide solutions drastically reduces the damage (Castro-García et al. 2015; Morales-Sillero et al. 2014; Zipori et al. 2014, 2021), although requires of appropriated resources and increases harvest costs. In fact, this is the common procedure in the super high-density commercial plantations of 'Manzanilla de Sevilla' that currently exist in Spain. It is noteworthy the null proportion of cut fruits and the least bruising incidence estimated from the percentage of fruits with severe bruising damage ($\leq 50\%$) observed in 2018. This could be related to the lower environmental temperature at the harvest time. In all seasons, the harvest was carried out at dawn, but the environmental temperature was 13 °C in 2018, about 4 and 5 °C less than in 2019 and 2020, respectively. Recently, it has been reported that low temperatures at harvest contribute to reducing the damage in 'Manzanilla de Sevilla' olive fruit when harvested mechanically in high-density orchards (Morales-Sillero et al. 2023). Besides, although 'Manzanilla the Sevilla' is currently employed in super high-density table olive orchards in Spain, the suitability of other alternative

traditional cultivars, such as ‘Hojiblanca’, and new olive bred genotypes are currently being evaluated under this growing system (Rallo et al 2020).

Conclusions

Rehydration was very important in the yield response from both treatments. Irrigation scheduling based on water status measurements improved the fruit quality in comparison to the farm strategy, and this is the most valuable yield feature. The enhancement in fruit size was likely related to a decrease in the stress integral during this period and could help the decision making about irrigation scheduling in deficit irrigation as in the current work. In addition, the monitoring of water status during the first period of fruit development would improve the vegetative development, which was likely related to the higher yield of RDI. However, high fruit damage in both irrigation managements was observed, confirming that ‘Manzanilla de Sevilla’ was very susceptible to this kind of harvest, even under better conditions for the fruit skin.

Acknowledgements With these words, we want to recognize the valuable collaboration of Prof. María Paz Suárez. We want also to thank Aceitunas Guadalquivir S.A. and Javier del Barco for the access they provided to the orchard and for their technical support. This study was partially supported by the project FIUS19/0049. We thank Jesús Ayén, Virginia Domínguez, Ana Tobar and Santiago de Mingo for their technical support.

Author contributions A.M.S., A.G., M.M.P and A.M. designed the experiment and measurements and treatments. A.M.S., A.G., L.C., P.R. and R.J. carried out field and laboratory measurements. All authors processing and analysed data. A.M.S., L.C. and A.M. prepared figures. A.M.S. and A.M. wrote the main manuscript text. All authors reviewed the manuscript.

Funding Funding for open access publishing: Universidad de Sevilla/CBUA.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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