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Effects of Regulated and Continuous Deficit Irrigation on Growth and Yield of Super High Density Olive orchard in La Rioja (Spain)

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Abstract

This study evaluated four irrigation strategies applied to olive trees (*Arbequina* cv.) in super high density orchard, in order to reduce the consumption of water compared to a fully watered control. The most advantageous strategy has been to prevent the water stress of trees by means of the continuous measurement of trunk diameter fluctuations in which the productive and vegetative variables are not altered with a 31.2 % of average water saving. The production of moderate stress during the pit hardening phase has also been very interesting. Experience shows that trees recover from this moderate stress (18.9 % average water saving) and their vegetative and productive characteristics turn out to be very similar to those of the control treatment.

On the contrary, the strategy that has been based on producing water stress throughout the crop, as well as that which produced severe stress during the pit hardening phase have been shown to significantly alter some of the vegetative and production characteristics. It caused a decrease in oil yield of 16% less compared to the Control, which might not compensate for the water saved.

Keywords: Regulated deficit irrigation, dendrometer, olive oil.

1. Introduction

Over the last years, olive growing has experienced a huge development. Plant densities are changing from 60-100 plants per hectare for wide spacing traditional olive orchards to 1600-2500 plants per hectare for super high density olive orchards. However, current super high density olive orchards increase plant spacing varying from 550 to 850 plants per hectare for rainfed conditions and from 650 to 1150 plants per hectare for irrigated orchards (Todolivo, s.f.). Despite rainfed orchards started to be planted with this olive category, in many cases, irrigation water is required to achieve stablished growth and yield objectives.

The Mediterranean area of cultivation and, in particular, La Rioja, is characterized by suffering from water deficit during the summer. Frequently, plant-watering demand cannot be satisfied with the available resources, so it is necessary to use Continuous Deficit Irrigation (CDI) strategies that remove part of the irrigation water during the entire vegetative cycle, or Regulated Deficient Irrigation (RDI), in which irrigation water amounts are reduced during phenological periods that are non-critical for yield or fruit quality. In the case of the olive tree, it coincides with the pit hardening phase, which takes place in the summer months.

In recent years, some experiments have been conducted to test RDI during the pit hardening phase (Goldhamer, 1999; Motilva et al., 2000; Tovar et al., 2002; Alegre et al., 2002) and continuous deficit irrigation (CDI) (Patumi et al., 2002; Tognetti et al., 2006; Goldhamer et al., 2006). However, these two irrigation strategies have not been compared between them. The studies report no or small differences in yield between fully and deficit irrigated trees. However, the evapotranspiration (ET) was not measured, so the results cannot be easily extrapolated to other situations.

Moriana et al. (2003) compare deficit irrigated trees under CDI and RDI to fully irrigated trees and reported that both deficit irrigation strategies reduce the ET and, consequently, the yield. These authors find an asymptotic yield-ET function, which means that water use efficiency (WUE) is reduced when the amount of irrigation increases. However, ET is different in both deficit irrigation strategies due to different amounts of irrigation applied in CDI and RDI.

On the one hand, Melgar et al. (2008) find no vegetative or productive responses to different irrigation regimes. On the other hand, Grattan et al. (2006) obtain the opposite results. It is demonstrated that less irrigation provokes a reduction in photosynthetic activity, although it does not affect productivity (Kremer et al., 2018) Therefore, definitive conclusions on the performance of the two strategies cannot be deduced.

The aim of the present study was to evaluate the effect of four deficit irrigation treatments productive and vegetative response of a super high density olive orchard cv. “Arbequina”. Flowering, number of fruits and oil yield was also assessed to optimize olive water demand.

2. **Materials and Methods**

2.1. Site description.

The experiment was conducted during 3 irrigation seasons from April to December (2006, 2007 and 2008) on a commercial olive orchard located in La Rioja (Spain) (42º 14´57.73" N; 2º 2´58.45" W) trees were 4 years old olive trees and they were drip irrigated. The climate of the zone is continental Mediterranean-type. The average year temperature for the experimental period was 13.8, 13.0 and 13.7 ºC respectively, although summer temperatures often exceed 32ºC. Rainfall during tested seasons were 417 (2006), 416 (2007) and 560 mm (2008) and most rains occurred during non-summer months. ET0 was 1085 (2006), 1047 (2007) and 991 mm (2008).

Olive trees *(Olea europaea)* variety Arbequina i-18 were planted with GPS at high density of 1666 trees ha^{-1} at 4.0 x 1.5 m spacing. Soil was sampled to obtain representative analysis values, soil deep was enough (> 1.5 m), with a loam-clay-sandy texture, alkaline pH, low organic matter and high calcium carbonate content (table 1). Crop management (fertilization, pruning, weed control, tillage and soil maintenance) was carried out following standard grower practices.

Table 1. Soil analysis results in March 2006.

Determinations	Value at 30 cm depth	Value at 60 cm depth
pH	7.9	8.18
Organic matter content (%)	1.3	0.7
Calcium carbonate content (%)	17.8	-
Field capacity (%)	29	28
Permanent wilting point (%)	9	10
Hydraulic conductivity (cm h^{-1})	3.9	1.6
Bulk density (kg m^{-3})	1.52	1.44

2.2. Experimental design and irrigation treatments description

The trial design consisted of a randomized complete block, with 5 treatments of irrigation and 3 repetitions. There were 15 plots in which 7 trees per plot located in a single row with two adjacent guard rows were selected for the measurements.

ETc for Control treatment was calculated according to:

$$ETc = ET0 \times Kc \times Kr \qquad (1)$$

ET0 was calculated using the Penman-Monteith-FAO method (Allen at al., 1998) from an automatic weather station close to the experimental plot. An estimated crop coefficient *Kc=0,7* was taken from Girona, J. (1996) for an intensive crop in full production as we have a perennial leaf crop, and a reduction coefficient (*Kr*) (Fereres and Castel, 1981) was considered to account the area shaded by the canopy. The *Kr* applies to canopies less than 50% ground cover and is described as:

$$Kr = 2 \times Sc/100 \qquad (2)$$

Where *Sc* is the percentage of canopy cover. Measurements made in April 2006 gave *Sc* = 37,5 %, so it was taken as a constant the value of *Kr = 0,75* for the three years of study.

Certain developmental periods in olive are especially sensitive to low soil moisture. Following Girona et al. (2004), during bloom period, olive is very sensitive to dry soil conditions, particularly in warm-dry weather. These conditions also cause excessive fruit thinning, fruit drop and alternate bearing. On the other hand, when moderate water deficit are suffered during the early stages of fruit development, fruit growth is not reduced compared with fully irrigated trees. However, water deficits during the final stages of fruit growth cause a reduction of fruit diameter reducing yield. Those moments were considered for the irrigation scheduling of RDI treatments.

So, from April to early June (growing of inflorescences and flowering period) no deficit was allowed, in order to obtain better flowering and more shoots for the following year. This water status was maintained during spring up to massive pit hardening phase which used to take place in June. From that moment to the beginning of fruit ripening, sensibility to water deficit was expected to be less important because of stomata closing due to high daily Vapor Pressure Deficit (VPD). Thus, during the summer vegetative growth stop, irrigations were limited to those that maintained the photosynthetic functions of leaves. From September to October (fruit ripening and reserve accumulation) water stress sensibility is maximum again, so deficit should be avoided.

Having into account these premises, irrigation treatments were defined as follows:

- T1: Control treatment (C): 100% ETc during the whole irrigation season.
- T2: Moderate regulated deficit irrigation (MRDI): 100% ETc from the beginning of season to massive pit hardening, 50% ETc during summer vegetative growth stop and 100% ETc from the ripening of fruit to the end of season.

- T3: Severe regulated deficit irrigation (SRDI): 100% ETc from the beginning of season to massive pit hardening, 25% ETc during summer vegetative growth stop and 100% ETc from ripening of fruit to the end of season.
- T4: Continuous deficit irrigation (CDI): 50% ETc the whole irrigation season.
- T5: Dendrometer regulated deficit irrigation (Dendro): Irrigation after two consecutive days of decrease of trunk diameter according to dendrometer data (Verdtech dendrometer, Verdesmart CO S.L., Spain) during summer vegetative growth stop. The volume of water contributed to each irrigation was equivalent to the ETc of the previous day. For the rest of the season, 100% ETc was used to irrigate.

2.3. Vegetative Measurements

At the beginning of the experiment, five central trees on each plot were marked to be taken as control trees. Measurements of plant growth consisted on tree height and trunk diameter 15 cm above the soil. At the same time, each season, two lateral branches from the upper third ones per tree were selected to measure its length. Measurements were performed at five different dates, at different phenological stages as follows: 15 days after shoot flush (I), pre-flowering (II), 5 weeks after fruit setting (III), beginning of ripening of fruit (IV) and pre-harvesting (V).

2.4. Production Measurements

Measurements were also made on selected branches (Table 2) to estimated flowering, fruit density (number of fruits per length of branch) and fruit set (percentage of initial flowers with fruit at harvest).

Table 2. Measurements and determinations of production carried out in the control trees along the vegetative growth season.

Measurements	I	II	III	IV	V
Number of inflorescences		X			
Number of flowers/shoot		X			
Number of fruits/ shoot			X		
Weight of 100 olives (g)			X	X	X
Ripening index (RI)					X

2.5. Data analysis

Results were analysed by an analysis of variance using the IBM SPSS Statistics 19.0 for Windows (IBM Corporation, Armonk, NY, USA). Differences and confidential levels were determined by calculating the least significant difference (LSD), and significant difference was defined at $p \leq 0.05$.

3. Results

3.1. Consumption of irrigation water

All irrigation strategies have achieved significant water savings compared to Control (Table 3). Higher savings were provided by CDI treatment, although all irrigation treatments provided significant differences ($\rho > 0{,}05$) compared to control treatment.

Table 3. Irrigation water applied (mm) and saving water (%) to the treatments during the three years of the experience. Treatments: Control treatment; MRDI, Moderate regulated deficit irrigation; SRDI, Severe regulated deficit irrigation; CDI, Continuous deficit irrigation; Dendro, Dendrometer regulated deficit irrigation. Different letters showed significant differences ($\rho > 0{,}05$) according to Duncan's test.

Treatments	mm/year	mm/year	mm/year	Average water saving (%)
Control	469.8	446.3	430.4	0.0 a
MRDI	383.5	360.8	348.1	18.9 b
SRDI	340.3	318.1	306.9	28.3 c
CDI	234.9	223.2	215.2	50.0 d
Dendro	327.4	306.1	292.5	31.2 c

3.2. Vegetative response

Regardless of the irrigation strategy, trees growth rapidly during phases I to III. Between phases III and IV (pit hardening) growth stops and, at the end of the summer, there is a second vegetative growth increasing. This seems to respond to the adaptation of the olive tree to the Mediterranean climate, which causes the stomas to close in periods of high temperatures and low relative humidity. Vegetative stop intensity seems to be affected by water management, which was more intense in the CDI, Dendro and SRDI treatments, and lower in the Control and MRDI treatment (Figure 1).

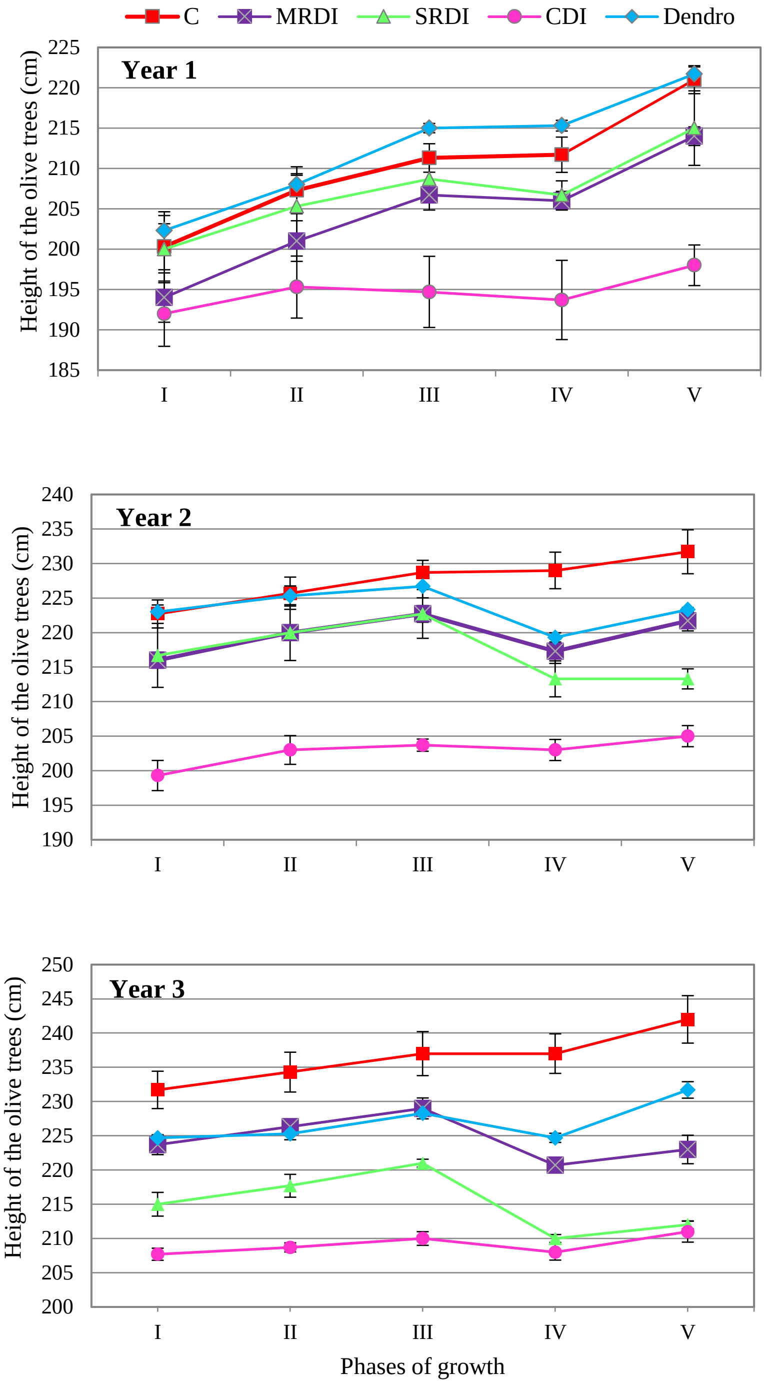

Figure.1. Evolution of the height of the olive trees (cm) in the different treatments of irrigation throughout the phases of growth in the three years of the experiment. The symbols represent the average of 15 measurements of three blocks and the vertical bars indicate the typical error.

A strong decrease in the growth height rate and in the length of lateral branches were observed in the CDI treatment that occurred from the first year (Table 4). This observation, which coincides with the data of Iniesta et al. (2009) and Moriana et al. (2003), seems to indicate that the sustained deficit affects growth adversely, which could be interesting to control vigour in Super high density olive orchards. In addition, SRDI shows a lower tree height and a shorter lateral branch length, although in the first year, differences were less evident. The treatments Control, MRDI and Dendro are the ones in which the plants reach greater height, and the side branches reach a greater length, without there being statistically significant differences between them.

Table 4. Absolute growth in tree height (cm) during the irrigation season in 2006, 2007 and 2008. Different letters showed significant differences (ρ> 0,05) according to Duncan's test.

Treatments	Absolute growth in tree height (cm) 2006	2007	2008
Control	20.7±3.5 a	9.0±2.1 a	10.3±1.2 a
MRDI	20.0±2 a	5.7±0.3 ab	-0.7±0.7 cd
SRDI	15.0±3.5 ab	-3.3±3.2 c	-3.0±1.2 d
CDI	6.0±1.5 b	5.7±0.7 ab	3.3±2.4 bc
Dendro	19.3±2.9 a	0.3±0.7 bc	7.0±1.5 ab

At the end of the three years of the experiment, the treatments Dendro and MRDI did not affect the height of the tree with respect to the Control. On the contrary, the trees of the CDI and SRDI strategies grew significantly below the previous ones after three years of testing. However, the irrigation strategies only showed a reduction of the thickness reached by the trunk at the end of the three seasons for CDI treatment (50% less), according to previous research, which find the same results: trunk growth is not affected by controlled deficit irrigation (Moriana et al. 2000).

Provided results showed that water restrictions during pit hardening seemed to affect the tree growth, that only took place for CDI treatment. Previous research was in accordance, for instance, Melgar et al. (2008) obtain a significant positive trend (ρ> 0,05) between length of the shoots and water applied in 3 of the 9 tested years. However, data showed that Control obtained the highest cumulative growth followed by Dendro and MRDI with no differences between them. SRDI obtained significant (ρ> 0,05) lower average growth than previous ones, and finally, CDI was placed with results similar to those obtained by Grattam et al. (2006) in which they observed smaller growths of the branches when they irrigated with doses inferior to 72% of the ETc during the entire vegetative cycle.

3.3. Flowers and fruits

The number of flowers per shoot did not changed significantly over time, but it does depend on the amount of water supplied (Table 6). On the contrary, it has been verified that in 2007 there were significant (ρ> 0,05) less fruits than in years 2006 and 2008, which leads us to think that alternate bearing phenomena described for the olive tree, although attenuated, are still present.

Table 6. Average of number of flowers and fruits per shoot, and fruit setting rate, at the end of the experiment. Different letters indicate significant differences (p< 0.05) between treatments according to Duncan's test.

Treatments	Number of flowers/shoot	Number of fruits/shoot	Fruit setting rate (%)
Control	716±63 ab	27.0±0.6 a	4.4±0.5 a
MRDI	675±37 ab	25.3±2.0 ab	3.9±0.5 a
SRDI	565±45 bc	20.9±1.7 bc	3.9±0.6 a
CDI	490±21 c	18.8±1.0 c	3.8±0.4 a
Dendro	738±83 a	29.4±2.5 a	4.2±0.8 a

At the end of the experiment, the irrigation strategies Dendro, Control and MRDI obtained a greater number of flowers per shoot without significant differences among them. By contrast, it was observed that CDI and SRDI had a lower number of flowers per shoot because the number of flowers per panicle was reduced (data not shown). Alegre et al. (2002) obtained similar results and concluded that the water deficit of one year could affect the flowering of successive years. In addition, when the influence of irrigation strategies was studied, it was observed that MRDI and Dendro provided no significant differences (ρ> 0,05) for number of fruits.

The results seem to indicate that floral induction phenomena occurring during the pit hardening phase at summer stop are not affected by treatments where the dendrometer is used as a reference and in which the stress is moderate. However, the moment that stress increases, the number of fruits suffers, which would explain the worse results of SRDI. Finally, the data suggest that, if the stress continues after the pit hardening phase in post-summer growth, the initiation phenomena would be affected, and the CDI treatment would have achieved its worst results. However, the rate of setting is not altered, which shows that the fruit set had not been influenced by the irrigation strategies.

Less clear seems to be the relation between the number of flowers and fruits and the vegetative growth of the shoots that Iniesta et al. (2009) indicate. Curdled fruits do not seem to be related to irrigation strategies in 2006 and 2007 (Table 7). Only in 2008 they separated, with the Dendro treatment producing more fruits per branch cm, while CDI had a lower yield.

Table 7. Number of flowers and fruits curdled per cm of branch during the three irrigation campaigns studied. Different letters indicate significant differences (p< 0.05) between treatments according to Duncan's test.

	Number of flowers/cm shoot			Number of fruits/cm shoot		
Treatments	2006	2007	2008	2006	2007	2008
Control	10.8±4.6 a	12.0±0.9 ab	14.7±1.4 a	0.46±0.0 a	0.39±0.1 a	0.52±0.0 ab
MRDI	9.2±0.5 a	12.6±1.0 ab	12.6±1.0 ab	0.47±0.1 a	0.36±0.0 a	0.51±0.0 ab
SRDI	10.6±2.5 a	9.6±0.9 bc	9.2±0.8 b	0.47±0.1 a	0.26±0.0 a	0.41±0.0 b
CDI	9.5±0.8 a	7.2±0.9 c	9.5±0.1 b	0.53±0.0 a	0.28±0.0 a	0.28±0.0 c
Dendro	14.3±3.3 a	14.2±1.8 a	14.2±0.4 a	0.53±0.1 a	0.38±0.0a	0.55±0.1 a

These data would indicate that the differences in the number of fruits would not be due to a higher rate of setting, but to a greater vegetative growth of the fruiting shoots in the Control, MRDI and Dendro strategies. As the shoot growth was greater, the number of fruits was also greater.

3.4. Yield

3.4.1.Evolution of the weight of 100 olives.

The evolution in time of fruit weight has not registered significant variations in the three years. The olives remained equal in size after ripening (III) apart from CDI, but during phases IV and V the fruits of the Control, Dendro and MRDI strategies accumulated more water and gained a greater weight of the olives at the harvest, while the CDI and SRDI treatments obtained significantly lower weights (Figure 2). These results coincide with those by Iniesta et al. (2009) who found that their treatments with deficits (similar to CDI and SRDI) reduced fruit growth. Tognetti et al. (2006) also found that deficit situations in the pit-hardening phase could affect linearly the weight of the fruit and, consequently, the final production.

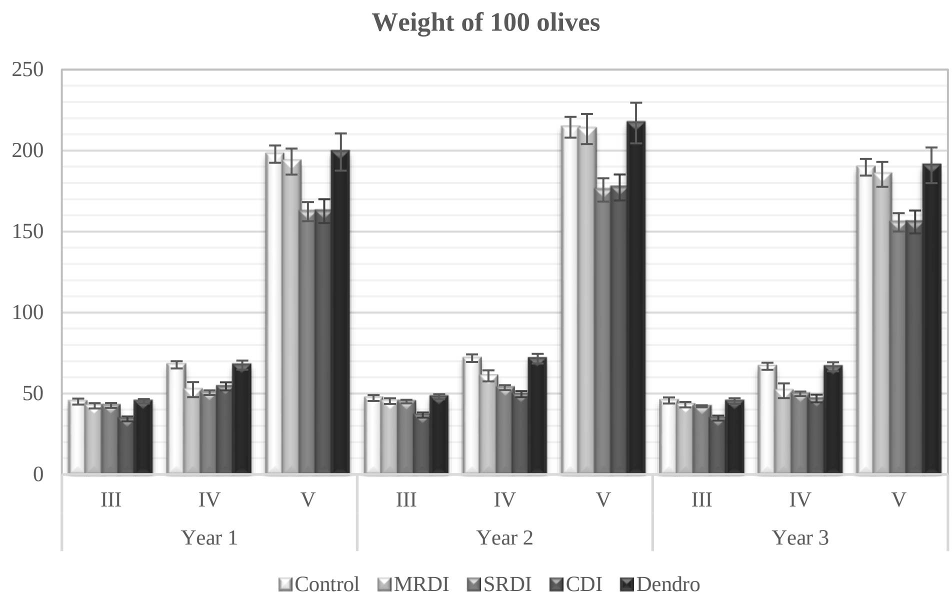

Figure 2. Evolution of the weight of 100 fruits (g) from the beginning of the summer vegetative stop (mid-July) (III) to the harvest (first of November) (V), in the three years of the experience, year 1 (2006), 2 (2007) and 3 (2008). The vertical bars represent the typical error.

The olives from CDI treatment always had lower weight, which seems to indicate that the continuous deficit negatively affects the weight of the fruits from the moment of their formation. Also, the SRDI and MRDI treatments increase less weight at time IV (fruit growth stage) than Dendro and Control. This seems to indicate that whatever the level of stress at that stage affects the growth of olives, a situation that has been visually verified in our case since we have observed fruit passages for the three deficit strategies at some point in time. MRDI treatment was capable of recovering the growth in weight in the moments prior to the harvest when the irrigation is restored, whereas SRDI treatment was not.

3.4.2. Production of oil

The production shows annual differences, so that the year 2007 is significantly less productive than 2006 and 2008. This seems to have to do with the data of a smaller number of fruits in that year.

The trees that were not undergone to water stress (Control and Dendro) achieved an olive production significantly ($p < 0.05$) superior to the rest because of having a greater number of fruits and a greater weight of the olives at harvest. It led to think that greater vegetative development of the productive shoots and increase of the fruit weight were decisive in the final production. According to showed results, Iniesta et al. (2009) also attribute to a lower vegetative growth the reduction of the harvest that they find when irrigation reduces tree growth.

Unlike with the production of olives, the oil yield was higher in more stressed treatments SRDI and CDI and lower in the rest of the irrigation treatments. However, the maximum oil production was achieved with the controlled deficit irrigation strategies Dendro and MRDI, without significant differences ($p < 0.05$) with the Control for yearly production. (Table 8). Similar results were obtained by Girona et al. (2002), which seem be related to the water content of the samples. The production of olive oil accumulated throughout the experiment has also been calculated in order to avoid the distortions that could be produced by the fact that the annual yields are different.

Table 8. Oil production per unit area (Kg oil /ha) for the different irrigation strategies in the three years of experience (Years 2006, 2007 and 2008) and cumulative production of the three years. Different letters indicate significant differences ($p < 0.05$) between treatments according to Duncan's test.

	Oil yield (Kg olive oil/ha)			
Treatments	2006	2007	2008	Cumulative
Control	1196±53.1 a	1075±21.9 a	1438±47.4 ab	3708±30 ab
MRDI	1090±24.4 ab	1037±63.7 ab	1496±80.7 a	3622±115 b
SRDI	963±20.9 b	880±19.0 b	1271±45.1 bc	3114±56 c
CDI	1018±9.8 b	911±51.8 b	1171±20.5 c	3100±81 c
Dendro	1198±64.5 a	1153±68.5 a	1614±79.3 a	3965±116 ab

4. Conclusions

The experiments carried out in a super high density olive orchard showed that there is room to optimize olive irrigation, considering that it is possible to reduce water applied without reducing olive growing nor oil production. Olive oil production in super high density olive orchards depends fundamentally on the vegetative development of the fruiting branches, the fruit set, and the evolution of the fruit weight until the harvest date.

The proposed irrigation strategy Dendro, in which the tree is watered when it is expected to suffer stress, with daily trunk diameter growth acting as an indicator, has obtained olive and oil yields like the fully irrigated Control treatment, providing mean water savings of 31.2 %. Data showed that this water saving strategy was possible because there has been no significant reduction in vegetative growth nor in the production of flowers and fruits. At the same time, olive weight in the summer deep similar to fully irrigated treatment. In the same way, the MRDI strategy has been interesting to achieve water savings of 18.9 % compared to Control. The vegetative parameters have decreased slightly with respect to Control, but not the weight of the olives in the harvest. Finally, SRDI and CDI treatments have altered the length of the shoots and the final weight of the olives, so that, despite achieving significant water savings, they provided lower oil production.

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