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How Could Precision Irrigation Based on Daily Trunk Growth Improve Super High-Density Olive Orchard Irrigation Efficiency?

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Abstract: Water deficit, especially during summer, is currently one of the most important stress factors that influence olive oil production in olive orchards. A precision irrigation strategy, based on daily trunk growth, was assessed and compared with one continuous deficit, one full irrigation, and two different regulated deficit irrigation strategies. All of them were tested in a super high-density olive orchard located in northeast Spain, in which oil production, main oil production components, applied irrigation water, and water productivity were assessed. For this purpose, the crop was monitored from budding to harvesting, mainly during the summer months in which the Precision strategy only applied water after two days of negative daily trunk growth. Maximum monthly water savings for the Precision strategy reached 91.8%, compared with full irrigation, while major annual mean water savings reached 50% for the continuous deficit strategy and 31.2% for the Precision strategy, which also reduced irrigation events by up to 19.7%, compared with the full irrigation strategy. Oil production and oil production components varied depending on the irrigation strategies providing the Control, one of the regulated deficit irrigations, and Precision higher values than the other strategies; oil yield results differ, nonetheless. The Precision strategy showed an overall better performance. Despite this, it did not achieve the highest water saving, it achieved higher water productivity.

Keywords: regulated deficit irrigation; continuous deficit irrigation; dendrometer; water productivity; water use efficiency and olive oil production components

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1. Introduction

Over the last years, olive growing has experienced a huge development. Plant densities are changing from 60 to 100 plants per hectare for wide spacing traditional olive orchards, and up to 1600–2500 plants per hectare for super high-density olive orchards. Current super high-density olive orchards have increased plant spacing, varying from 550 to 850 plants per hectare for rainfed conditions, and from 650 to 1150 plants per hectare for irrigated orchards. This change in plant spacing in new super high-density olive orchards reduces investment requirements from 40% to 70% and it reduces crop costs by around 30% [1]. Despite being rainfed, orchards are being planted in super high-density olive plantations, and in many cases, irrigation water is required to achieve established growth and yield objectives.

The Mediterranean area of cultivation is characterized by suffering from water deficit during the summer, which is one of the expected drivers for climate change impact on Mediterranean olive orchards, increasing the chilling and heat effects [2]. Frequently, plant-watering demand cannot be satisfied with the available resources, so it is necessary to reduce water consumption. Two strategies to save water can be applied: continuous deficit irrigation (CDI), which remove part of the irrigation water during the whole irrigation season, and regulated deficit irrigation (RDI), in which irrigation is reduced during non-critical yield stages or drought-tolerant periods. For olive trees, these periods coincide with the pit hardening phase, which takes place in the summer months. The RDI strategy could increase olive orchard sustainability compared to common grower practices [3].

Some experiments have been conducted to test RDI during the pit hardening phase [4–7], and CDI [8–10]. On one hand, these studies about CDI and RDI strategies report no or small fruit production differences between full and deficit-irrigated trees. On the other hand, recent studies indicate that RDI provided higher water productivity and higher water savings compared to CDI [11], along with lower transpiration for the CDI strategy compared with full-irrigated trees [12]. However, irrigation strategies did not provide significant differences compared to fully irrigated olives for the olive oil amount per unit of photosynthetic active radiation (PAR) [13]. Nevertheless, olive interactions with the environment, such as tree genetics, pests, or diseases, are complex [12]; therefore, further research is required to assess olive behavior in different climate conditions.

On one hand, certain developmental periods in olive growth are especially sensitive to low soil moisture. For instance, during the bloom period, the olive tree is very sensitive to dry soil conditions, particularly in warm-dry weather [14,15]. These conditions usually cause excessive fruit thinning, fruit drop and alternate bearing. On the other hand, when olive trees suffer moderate water deficit, after pit hardening, fruit growth does not show significant reductions compared with fully irrigated trees. However, water deficits during the final stages of fruit growth cause a reduction in fruit diameter and oil yield, while RDI irrigation could increase oil yield, oil polyphenol content, and facilitate mechanical harvesting by keeping compact canopies [16]. Nevertheless, results are not conclusive about vegetative and productive responses to different irrigation regimes because, in some cases, differences have not been found [17] while other experiments show opposite results [18]. Therefore, definitive conclusions on the yield performance of the two strategies cannot be established thus far, considering that less irrigation provokes a reduction in photosynthetic activity, although it does not affect productivity [19]. Furthermore, environmental issues, such as water or energy savings, have steadily increased their relevance. In this sense, CDI and RDI strategies reported a reduction in evapotranspiration (ET) compared to a full irrigation strategy due to different amounts of applied water. This relationship follows an asymptotic yield-ET function, which means that water use efficiency (WUE) is reduced when the amount of irrigation increases [20].

The aim of the present study was to evaluate the effect of four deficit irrigation strategies and an additional full irrigation strategy on a super high-density olive orchard cv. “Arbequina” in order to optimize water management, considering both oil production and irrigation water savings. Flowering, number of fruits, and oil yield were also assessed to select an optimized irrigation strategy to reduce water demand without reducing oil production.

2. Materials and Methods

2.1. Experimental Site Description

The experiments were conducted during 3 irrigation seasons from April to December on a commercial olive orchard located in La Rioja (Spain) (42°14′57.73″ N; 2°2′58.45″ W). Trees were drip-irrigated, and they were 4 years old at the beginning of the test; therefore, tests were conducted during the fourth, fifth, and sixth growing years. The climate of the zone is a continental Mediterranean type. The average year temperature for the experimental period was 13.8, 13.0, and 13.7 °C, respectively, although summer temperatures often exceed 32 °C. Potential evapotranspiration (ET_0) was 1085, 1047, and 991 mm for each of the 3 years considered.

The selected plot was composed of super high-density hedge-pruned olive trees *(Olea europaea)* of the variety Arbequina i-18, which were planted at 4.0 × 1.5 m spacing. Orchard management was carried out following standard grower practices, being uniform except for irrigation. We took soil samples at 1.5 m depth throughout the plot to obtain representative samples for soil analysis, which provided a loam-clay-sandy texture, alkaline pH, low organic matter and high calcium carbonate content (Table 1).

Table 1. Soil analysis results before the tests start. Showed values were the mean of the samples.

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 Strategies

Experiments consisted of 3 replications of 5 irrigation strategies following a randomized complete block design. Each experimental unit was composed of 7 trees located in a single row, keeping 2 adjacent guard rows. Furthermore, both end trees of the 7 trees selected were dismissed, taking tree and fruit measurements only from 5 trees.

Crop evapotranspiration (ET_c) for the Control treatment was calculated according to Equation (1).

$$ET_c = ET_0 \times Kc \times Kr \tag{1}$$

We calculated ET_0 using the Penman–Monteith–FAO method [21] using data from an automatic weather station set up in the same orchard in the experimental plot. Crop coefficient Kc = 0.7 [22] was estimated for an intensive crop in full production as we had a perennial leaf crop, and a reduction coefficient (Kr) [23] was considered to account for the area shaded by the canopy. The Kr applied to canopies that covered less than 50% of the ground and was calculated according to Equation (2):

$$Kr = 2 \times Sc/100 \tag{2}$$

where Sc is the percentage of canopy cover. Measurements made the first year of the tests gave Sc = 37.5%, so it was taken as a constant as the value of Kr = 0.75 for the three years of study.

Based on previous experiences, RDI strategies received full water needs from April to early June (growing of the inflorescences and the flowering period), keeping no differences with the fully irrigated control treatment, in order to obtain better flowering and more shoots for the following year. This water status was maintained during spring up to the massive pit hardening phase, which used to take place in June. From that moment to the beginning of fruit ripening, a sensitivity to water deficit was expected to be less important. This effect took place because of the stomata closing, provoked by the high daily vapor pressure deficit (VPD). Thus, vegetative growth stopped during the summer, and then irrigations were limited to those that maintained the photosynthetic functions of leaves. From September to October (fruit ripening and reserve accumulation period, respectively) the water stress sensibility was maximum again and, therefore, the RDI strategy received full water needs again.

Regarding these premises, irrigation strategies were defined as follows:

- Control strategy (Control): 100% ET_c during the whole irrigation season;
- Moderate regulated deficit irrigation (MRDI): 100% ET_c from the beginning of the season to massive pit hardening, 50% ET_c during summer vegetative growth stop, and 100% ET_c from the ripening of fruit to the end of the season;
- Severe regulated deficit irrigation (SRDI): 100% ET_c from the beginning of the season to massive pit hardening, 25% ET_c during summer vegetative growth stop, and 100% ET_c from the ripening of fruit to the end of the season;
- Continuous deficit irrigation (CDI): 50% ET_c the whole irrigation season;
- Data-based precision irrigation (Precision): During summer vegetative growth stop, trunk diameter was measured every day, and water was applied after two consecutive

days in which trunk diameter was decreasing according to dendrometer data (Verdtech dendrometer, Verdesmart CO S.L., Huelva, Spain). The water amount in each irrigation during this period was equivalent to the ETc of the previous day. For the rest of the season, 100% ET_c was applied to irrigate.

2.3. Vegetative, Flowering, and Production Measurements

At the beginning of the experiment, besides 5 selected trees for each replication, 5 central trees on each replication were marked as control trees. We took measurements of trunk diameters 15 cm above the soil, fruit size, ripening index along with inflorescences, flowers and fruits set per shoot. Time to take measurements comprised 5 different phenological stages as follows: 15 days after budding (I), pre-flowering (II), 5 weeks after fruit setting (III), beginning of fruit ripening (IV), and pre-harvesting (V) (Table 2).

Table 2. Measurements and determinations of production were carried out in all tested trees along the vegetative growth season. X means that measurements were taken in this phenological stage.

Measurements	I	II	III	IV	V
Branch length	X	X	X	X	X
Number of inflorescences		X			
Number of flowers shoot^{-1}		X			
Number of fruits shoot^{-1}			X		
Weight of 100 olives (g)			X	X	X
Ripening index (RI)					X

At harvest, fruits from one tree per plot were harvested to measure fruit production. Moreover, oil from the fruit sample was extracted using an Abencor® laboratory set for olive analysis (Mc2, Spain) [24] to calculate the oil yield according to Equation (3).

$$\text{Oil yield } (\%) = \frac{\text{extracted oil from fruit sample } (\text{mL}) * 0.915}{\text{kneading paste weight } (\text{g})} * 100 \tag{3}$$

Water productivity (WPI) was also assessed using oil production and the amount of irrigation water applied [25] according to Equation (2).

$$\text{WPI} = \text{Yield } (\text{kg ha}^{-1}) / \text{Irrigation Water Applied } (\text{m}^3\ \text{ha}^{-1}) \tag{4}$$

2.4. Data Analysis

Results were analyzed by an analysis of variance using the 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 a 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 ($p \leq 0.05$) compared to the Control strategy (Table 3). Higher water savings were achieved with continuous deficit irrigation followed by data-based irrigation along with severe regulated deficit irrigation.

Precision irrigation strategy was regulated based on daily trunk diameter measurements. When daily trunk growth decreased during two consecutive days, irrigation was applied using an amount of water corresponding to 100% of the previous day ET_c (Figure 1). The Precision strategy schedule made it possible to reduce irrigation events from 19.7% to 26.2% (Table 4) of the total days, limiting irrigation systems starts and soil surface humectation time.

Table 3. Annual values of potential evapotranspiration (ET_0), rainfall (R), irrigation water applied (mm), and water saving (%) for the irrigation strategies during the three years of the experiments. (MRDI: moderate regulated deficit irrigation; SRDI: severe regulated deficit irrigation; CDI: continuous deficit irrigation). Different letters showed significant differences ($p \leq 0.05$) among treatments according to Duncan's test.

	Year 1		**Year 2**		**Year 3**		
ET_0 (mm)	1085		1047		991		
R (mm)	416.8		425.6		560.4		
Strategies	**mm/year**	**Saving (%)**	**mm/year**	**Saving (%)**	**mm/year**	**Saving (%)**	**Average water saving (%)**
Control	469.8	0.0	446.3	0.0	430.4	0.0	0.0 d
MRDI	383.5	18.4	360.8	19.2	348.1	19.1	18.9 c
SRDI	340.3	27.6	318.1	28.7	306.9	28.7	28.3 b
CDI	234.9	50.0	223.2	50.0	215.2	50.0	50.0 a
Precision	327.4	30.3	306.1	31.4	292.5	32.0	31.2 b

Table 4. Number of irrigation events during summer (July and August) for the Precision irrigation strategy compared with the rest of strategies.

Strategies	**Year 1**	**Year 2**	**Year 3**
Precision irrigation	12	16	12
Other irrigation strategies	61	61	61

During summer (July and August), daily trunk growth data was used to support irrigation decisions reducing water consumption in comparison with the rest of the irrigation strategies, except for CDI, for which the total amount of water was lower (Table 5).

Table 5. Monthly irrigation volume (mm) for each irrigation strategy during three tested years. (MRDI: moderate regulated deficit irrigation; SRDI: severe regulated deficit irrigation; CDI: continuous deficit irrigation).

Year 1 (mm/Month)								
Strategies	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**Total**
Control	53.0	72.2	86.8	91.9	80.6	50.2	35.0	469.8
MRDI	53.0	72.2	86.8	46.0	40.3	50.2	35.0	383.5
SRDI	53.0	72.2	86.8	23.0	20.2	50.2	35.0	340.3
CDI	26.5	36.1	43.4	46.0	40.3	25.1	17.5	234.9
Precision	53.0	72.2	86.8	11.6	18.6	50.2	35.0	327.4
Year 2 (mm/Month)								
Strategies	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**Total**
Control	46.8	64.6	73.8	92.6	78.3	57.3	33.0	446.3
MRDI	46.8	64.6	73.8	46.3	39.2	57.3	33.0	360.8
SRDI	46.8	64.6	73.8	23.2	19.6	57.3	33.0	318.1
CDI	23.4	32.3	36.9	46.3	39.2	28.6	16.5	223.2
Precision	46.8	64.6	73.8	22.0	21.6	49.1	28.3	306.1
Year 3 (mm/Month)								
Strategies	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**Total**
Control	59.1	52.7	72.2	86.0	78.6	53.0	28.8	430.4
MRDI	59.1	52.7	72.2	43.0	39.3	53.0	28.8	348.1
SRDI	59.1	52.7	72.2	21.5	19.7	53.0	28.8	306.9
CDI	29.53	26.4	36.1	43.0	39.3	26.5	14.4	215.2
Precision	59.06	52.7	72.2	7.0	19.8	53.0	28.8	292.5

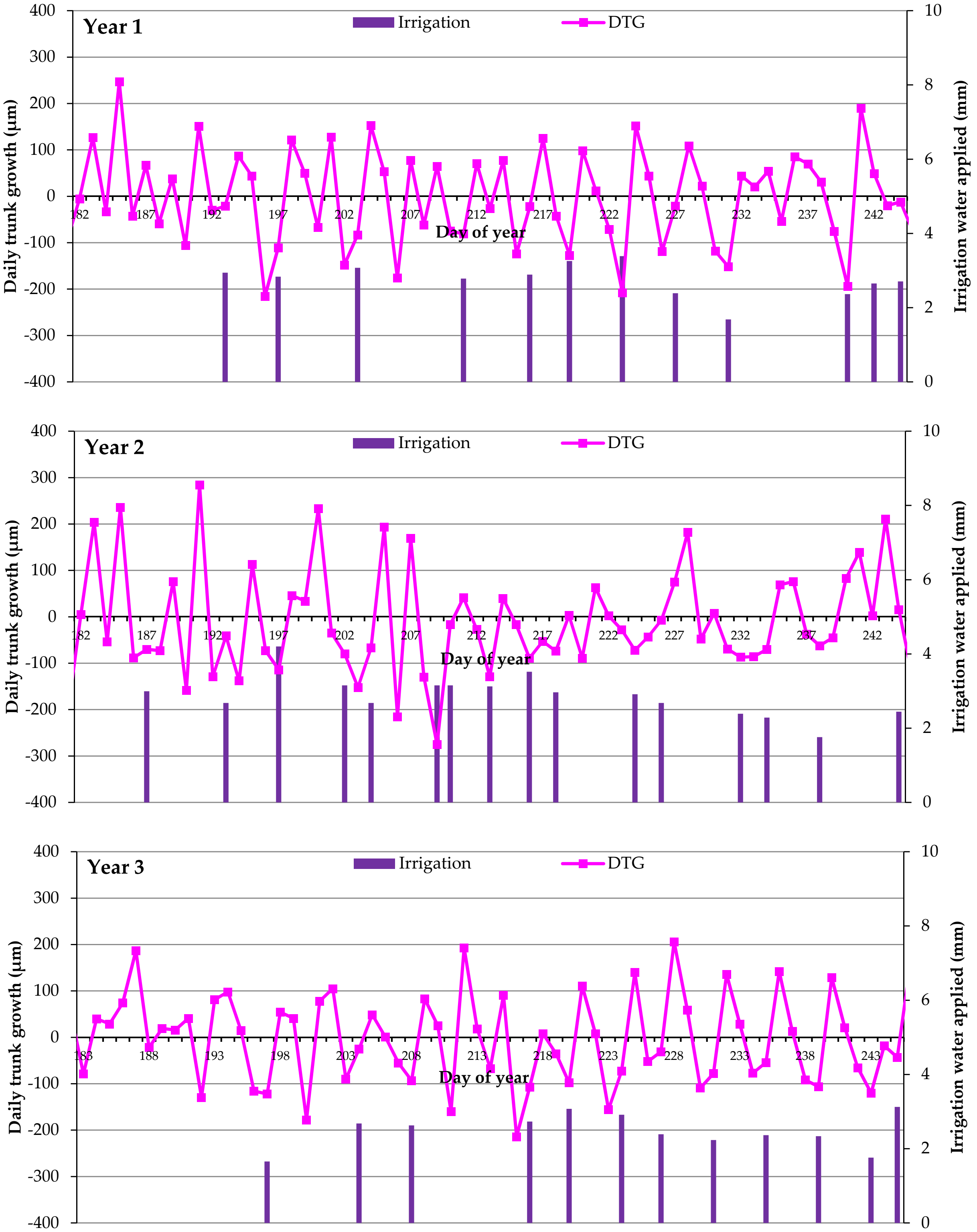

Figure 1. Daily trunk growth (DTG) during summer (µm/day) was used to support the decision-making process for Precision irrigation during three tested years. Bars represent the date and amount of water applied during each irrigation. The *X*-axis represents the day of the year.

3.2. Olive Oil Production Components

On one hand, the number of flowers per shoot did not change significantly over time, but it varied depending on the amount of water supplied (Table 6). On the other hand, it was verified that in year 2 there were significantly fewer fruits than in years 1 and 3

($p \leq 0.05$), which led us to think that alternate bearing phenomena described for the olive crop, although attenuated, were still present.

Table 6. Average of the number of flowers and fruits per shoot, and fruit setting rate at the end of the experiment. (MRDI: moderate regulated deficit irrigation; SRDI: severe regulated deficit irrigation; CDI: continuous deficit irrigation). Different letters showed significant differences ($p \leq 0.05$) among treatments according to Duncan's test.

Strategies	Number of Flowers per Shoot	Number of Fruits per Shoot
Control	716 ± 63 ab	27.0 ± 0.6 a
MRDI	675 ± 37 ab	25.3 ± 2.0 ab
SRDI	565 ± 45 bc	20.9 ± 1.7 bc
CDI	490 ± 21 c	18.8 ± 1.0 c
Precision	738 ± 83 a	29.4 ± 2.5 a

Absolute growth in lateral branches provided significantly higher values for the Control, MRDI and Precision strategies for year 1 and year 3. The same trend was observed for the average number of fruits per year and the number of flowers each year (Figure 2) per shoot length (Table 7). Data indicate that the differences in the number of fruits were not due to significant differences in fruit setting rate, but to a greater vegetative growth of the fruiting shoots in the Control, MRDI and Precision strategies. As the shoot growth was greater, the number of fruits was also greater.


(**a**) (**b**)

Figure 2. Inflorescences are composed of several flowers during bloom (**a**) and after fruit set and the first fruit falling at the beginning of summer (**b**).

Table 7. The number of flowers per cm of branch and fruit setting rate (%) during three tested years. (MRDI: moderate regulated deficit irrigation; SRDI: severe regulated deficit irrigation; CDI: continuous deficit irrigation). Different letters showed significant differences ($p \leq 0.05$) among treatments for the same year according to Duncan's test.

	Number of Flowers per cm Shoot			Fruit Setting Rate (%)		
Strategies	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Control	10.8±4.6 a	12.0 ± 0.9 ab	14.7 ± 1.4 a	6.2 ± 1.8 a	3.3 ± 0.6 a	3.6 ± 0.3 a
MRDI	9.2±0.5 a	12.6 ± 1.0 ab	12.6 ± 1.0 ab	5 ± 1.0 a	2.8 ± 0.2 a	3.9 ± 0.4 a
SRDI	10.6±2.5 a	9.6 ± 0.9 bc	9.2 ± 0.8 b	4.7 ± 1.3 a	2.6 ± 0.4 a	4.3 ± 0.4 a
CDI	9.5±0.8 a	7.2 ± 0.9 c	9.5 ± 0.1 b	5.5 ± 0.8 a	3.3 ± 0.4 a	2.7 ± 0.2 a
Precision	14.3±3.3 a	14.2 ± 1.8 a	14.2 ± 0.4 a	5.2 ± 1.3 a	3.1 ± 0.9 a	4.4 ± 0.5 a

Fruit weight evolution was measured over the three tested years. Significant differences ($p \leq 0.05$) among the irrigation strategies appeared along with fruit development, except for continuous deficit irrigation. Before harvesting, fruits from the Control, Precision and MRDI strategies accumulated more water and gained a greater fruit weight at harvest, while the CDI and SRDI strategies obtained significantly lower weights (Figure 3).

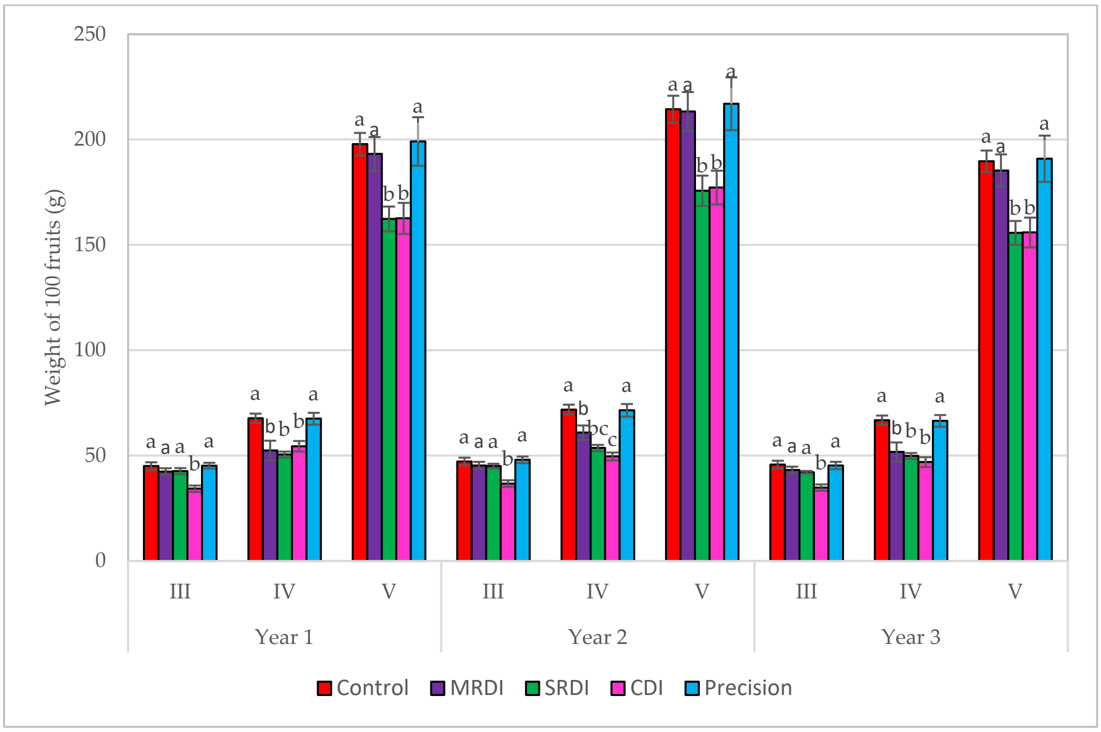

Figure 3. Evolution of 100 fruits' mean weight and standard deviation (g) from the beginning of the summer vegetative stop (mid-July) (III) to the harvest (first of November) (V), over three tested years. (MRDI: moderate regulated deficit irrigation; SRDI: severe regulated deficit irrigation; CDI: continuous deficit irrigation). Different letters showed significant differences ($p \leq 0.05$) among treatments for the same year according to Duncan's test.

The olives from the CDI strategy always had a lower weight, which seems to indicate that a continuous deficit negatively affects the weight of the fruits from the moment of their formation. In addition, the SRDI and MRDI strategies increase weight slower at the beginning of the ripening than the Precision and Control strategies. This seems to indicate that any stress at that stage affects the growth of olives, which was also observed in the field. However, the MRDI strategy could recover the growth in weight before harvest when irrigation began again, whereas the SRDI strategy was not able to recover fruit weight.

Oil production showed annual differences among the years, although the irrigation strategy clearly influenced it every year. Trees that did not undergo water stress (Control and Precision) along with MRDI, achieved significantly higher oil productions compared to other strategies ($p \leq 0.05$), while more stressed trees produced less oil (Table 8). Furthermore, SRDI and CDI achieved significantly lower fruit weights but higher oil yields, while the Control, MRDI and Precision provided inverse results, high fruit weights and low oil yields (Figure 3 and Table 9). However, oil yield on a wet basis showed higher variability.

Table 8. Olive oil production (kg ha^{-1}) for the different irrigation strategies in the three years of experience and cumulative production. Different letters indicate significant differences ($p \leq 0.05$) among treatments according to Duncan's test.

	Oil Production (kg ha^{-1})			
Strategies	**Year 1**	**Year 2**	**Year 3**	**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
Precision	1198 ± 64.5 a	1153 ± 68.5 a	1614 ± 79.3 a	3965 ± 116 ab

Table 9. Oil yield (%) measured by the Abencor® method at harvest in the three irrigation campaigns. Values were mean ± standard deviation. Different letters showed significant differences ($p \leq 0.05$) among treatments for the same year according to Duncan's test.

	Oil Yield at Harvest		
Strategies	**Year 1**	**Year 2**	**Year 3**
Control	21.3 ± 0.3 b	22.7 ± 0.5 c	20.8 ± 0.2 c
MRDI	20.5 ± 0.3 b	22.2 ± 0.5 c	24.3 ± 0.3 ab
SRDI	23.0 ± 0.5 a	26.6 ± 0.3 ab	25.7 ± 0.8 a
CDI	23.6 ± 0.3 a	28.2 ± 2.4 a	25.7 ± 0.7 a
Precision	21.6 ± 0.6 b	24.1 ± 1.3 bc	23.0 ± 1.0 b

3.3. Water Productivity

Water productivity was inversely related to irrigation volume, achieving significantly higher efficiency ($p \leq 0.05$) when irrigation volume was the lowest. The RDI strategy provided the best behavior in this sense, but it did not provide the highest oil production. Water productivity for the Precision strategy was softened by differences among the years. However, cumulative results provided significantly better water productivity ($p \leq 0.05$) compared with other irrigation strategies excluding CDI. The Control strategy always had the worst water productivity, which led us to state that any strategy used to save irrigation water could improve water productivity (Table 10). Furthermore, higher rainfall provoked higher water productivity in year 3, although further studies should be conducted to confirm this hypothesis.

Table 10. Water productivity was measured as olive oil weight per irrigation volume for different irrigation strategies during the three test years and cumulative value. Values were mean ± standard deviation. Different letters showed significant differences ($p \leq 0.05$) among treatments according to Duncan's test.

	Water Productivity (kg Olive Oil mm Irrigation^{-1})			
Strategies	**Year 1**	**Year 2**	**Year 3**	**Cumulative**
Control	2.55 ± 0.11 c	2.41 ± 0.05 c	3.34 ± 0.11 c	2.75 ± 0.02 c
MRDI	2.84 ± 0.06 c	2.87 ± 0.18 bc	4.30 ± 0.23 b	3.32 ± 0.11 b
SRDI	2.83 ± 0.06 c	2.77 ± 0.06 c	4.14 ± 0.15 bc	3.23 ± 0.06 b
CDI	4.33 ± 0.04 a	4.08 ± 0.23 a	5.44 ± 0.10 a	4.60 ± 0.12 a
Precision	3.66 ± 0.20 b	3.77 ± 0.22 b	5.52 ± 0.27 a	4.28 ± 0.12 a

Despite the high-water productivity achieved by the Precision strategy, it is important to remark that this strategy required some additional sensors and material in relation to the other strategies studied here. Table 11 illustrates the investment and maintenance costs for two different equipment levels of the Precision irrigation system per irrigation sector; the price information was obtained in March 2022 from a Spanish company who markets these products. For a low-cost precision irrigation strategy, data to assess ET_c should be obtained from public weather stations. However, the use of the Precision strategy could be easily adopted by farmers and technicians after a short learning process.

Table 11. Additional costs per irrigation sector for two different equipment levels to enable Precision irrigation strategy.

Description	Other Strategies	Low-Cost Precision Strategy	Full Equipment Precision Strategy
LPWAN or GSM modem to send data remotely	€0	€375 [1]	€1075 [2]
Access license and GSM link	€0	€120 $year^{-1}$	€120 $year^{-1}$
Maintenance fee	€0	€75 $year^{-1}$	€75 $year^{-1}$
Dendrometer	€0	€636	€636
Installation	€0	€100	€100
Pluviometer	€0	€0	€205
Anemometer	€0	€0	€185
Radiometer	€0	€0	€330
Temperature, humidity and pressure sensor	€0	€0	€195
Total investment	€0	€1111	€2726
Yearly maintenance fee	€0	€195 $year^{-1}$	€195 $year^{-1}$

[1] LPWAN (Low-Power Wire-Area Networks) or GSM (Global System for Mobile) modem until two sensors. [2] GSM modem until 14 sensors.

4. Discussion

Irrigation strategy influenced both water consumption and oil production, together with yield components. Firstly, the Precision, Control, and MRDI irrigation strategies 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 also lower (data not shown). This effect could be due to different stress levels for each irrigation strategy, considering that it is well known that a water deficit of one year could affect the flowering of successive years [6]. However, when the influence of irrigation strategies was studied, it was observed that the Control and Precision strategies provided no significant differences ($p \leq 0.05$) for the number of fruits per shoot. The number of fruits per tree is an important yield component to determine oil production [26], although it also provokes hormonal signals, which may affect floral induction [27].

Results indicate that the Precision irrigation strategy did not affect floral induction phenomena during the pit hardening phase at summer stops. It was due to the control of water deficit using a dendrometer to avoid severe stress events. Nevertheless, when the water deficit increased during sensitive periods, the number of fruits was reduced, as it took place for SRDI; water deficit provokes less pollination by hindering flower opening [15]. Finally, data suggest that if the water deficit continues after the pit hardening phase in post-summer fruit growth, oil production will be reduced due to a lower oil accumulation. However, the fruit setting rate did not show significant differences ($p \leq 0.05$), which demonstrated that the fruit set had not been influenced by the irrigation strategies [13,18]. Furthermore, fruit weight (Figure 3) and oil production (Table 8) showed significantly ($p \leq 0.05$) heavier fruits for the Control, MRDI and Precision strategies than for those strategies that provoked more severe water deficits, while the oil yield showed the opposite trend (Table 9). It is known that this fact is dependent on the amount of water applied; a 15 m^3 $tree^{-1}$ threshold has been observed for traditional 10 × 10 m spacing trees to get a significantly higher fruit and oil production, whereas fruit weight does not vary significantly [28] However, other studies report that irrigated olive trees under severe water deficits like CDI or SRDI reduced fruit growth [13], and those deficit situations during the pit hardening phase could linearly affect fruit weight and, consequently, fruit production [10]. Moreover, the fruit's size is related to the trunk growth rate during pit hardening, and yield reductions are likely related to fruit drop [29].

Cumulative olive oil production has been calculated (Table 8) throughout the experiment to avoid year influence on yield components, although yearly variability was highly useful for understanding olive productive behavior. Oil production depends on vegetative development through canopy volume or tree crown area [30], which could be modified by the pruning system, frequency, and/or pruning intensity [31]. Furthermore, fruit weight is decisive in the final production, as described in a previous study, which also considers that lower vegetative growth provokes a reduction in harvest when irrigation is shortened [13]. Despite differences in water consumption among strategies, a maximum oil production was achieved for the Control, Precision and MRDI strategies, without significant differences ($p \leq 0.05$) with the Control for yearly production. (Table 8), although water productivity showed higher mean values for CDI and the Precision strategies (Table 10). Productive, economic, and environmental approaches should be considered to assess irrigation strategies because water saving has an increasing relevance to mitigating climate change effects through regulated deficit irrigation [32]. However, different irrigation treatments provided different oil production (Table 9), while water productivity differences for treatments with the same oil productivity differed from 1.53 to 0.96 kg mm^{-1} of irrigation. Similar results were reported previously with fruit production differences among irrigation strategies until 1877 kg ha^{-1} per year [33]. Precision irrigation helped to increase oil and fruit production, which should cancel out yearly maintenance fees and the total investment required to establish this strategy.

5. Conclusions

Five different deficit irrigation strategies were assessed during three-year tests in a super high-density olive orchard. Monthly water savings occasionally reached 91.8% during summer for the Precision strategy, while a mean annual water saving varied from 50% for continuous deficit irrigation to 18.9% for moderate regulated deficit irrigation. However, the Precision strategy showed to be the best option when oil production optimization was considered, reaching annual water savings of up to 32%, while oil production was not reduced, compared with full irrigation or MRDI strategies. These benefits were reached by establishing the Precision strategy, which was based on a low-cost technology that only required dendrometers, data loggers and modems to gather and send collected data. Furthermore, water savings for this strategy took place in the summer months, when many other crops trigger irrigation water demand. Thus, the Precision strategy can be of great interest since, during this period, water sources are usually scarce in the Mediterranean areas.

Olive oil production, in super high-density olive orchards, depends on flowering, fruit setting rate, fruit weight and oil yield. These parameters should be monitored from flowering initiation until the harvest date. Different irrigation strategies provided significantly different ($p \leq 0.05$) numbers of flowers per shoot or per shoot length, and significantly different ($p \leq 0.05$) numbers of fruits, fruit weight and oil production. All these yield components made it possible to stack irrigation strategies into two main groups: Precision, Control and MRDI strategies provided higher values for these oil production components, which benefited oil production. Nevertheless, oil yield showed an opposite trend, compared to oil production components. However, this fact was not enough to equal the oil production components of SRDI and CDI strategies to the other group of strategies. Finally, the mean cumulative water productivity varied from 4.6 to 2.75 kg of oil per mm, depending on the irrigation strategy being the continuous deficit irrigation and Precision strategies, the ones with the highest water productivity. However, the highest cumulative oil production was provided by the Control and Precision strategies.

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