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Effects of regulated, precision and continuous deficit irrigation on the growth and productivity of a young super high-density olive orchard

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ABSTRACT

Water is the main limiting factor for olive cultivation in rainfed conditions. In irrigated orchards, water availability is scarce mainly during drought periods. Thus, increasing irrigation efficiency is a key issue to improve water management, especially in semiarid conditions. The objective of this study was to assess different irrigation strategies on tree growth and production components during three years in a young super high-density olive orchard (*Arbequina* cv.) located in northeast Spain. Four deficit irrigation strategies were compared to a control strategy based on replenishing crop evapotranspiration. The four strategies were as follows: Continuous Deficit Irrigation (CDI), two Regulated Deficit Irrigation strategies (Moderate, MRDI, and Severe, SRDI), and a precision Irrigation strategy based on daily trunk growth (Precision). In the Precision strategy, olive oil production increased by 7% and the vegetative variables did not show significant reductions, resulting in an average yearly water savings of 31% compared to the control strategy. The Regulated Deficit Irrigation strategies also produced promising results based on the high average yearly water-saving rates of 19% and 29%. However, the SRDI strategy exhibited significant reductions in tree height, lateral branches growth, olive yield, and oil yield compared to the control. On the other hand, the MRDI strategy did not differ significantly in oil yield, tree height, and lateral branches growth compared to the control or Precision strategies. Similarly, the CDI strategy resulted in significantly lower tree height, lateral branches growth, and production compared to the control. Although the observed reduced growth in both SRDI and CDI strategies presents an interesting opportunity for managing excessive vigor in super high-density olive orchards, it is important to consider that this approach may compromise production in successive seasons.

1. Introduction

Olive cultivation is generally concentrated in areas with a Mediterranean climate, which is characterized by mild rainy winters and warm dry summers. Spain leads olive production with an area of 2.77 million hectares of which 1.89 million are cultivated in rainfed orchards. The rest were grown under irrigation conditions (MAPA, 2021). In the rainfed conditions, water is the main limiting factor of the crop along with increasing temperatures. These factors make the rainfed low-density orchards in dry regions more vulnerable to climate change (Mairech et al., 2021). For this reason, planting densities have been very low in traditional olive cultivation. However, in the last 20 years, super high-density orchards have been planted; their density varies from 550 to 850 trees ha^{-1} in rainfed conditions and from 650 to 2000 plants ha^{-1} in irrigated orchards. In these orchards, trees were hedgerow trained to maximize production and reduce costs through mechanized harvesting (Connor et al., 2014; Rius and Lacarte, 2015). Super high-density orchard mechanical harvesting with straddle harvesters multiplies the effective field capacity by 2–7, compared to other harvesting systems (Castillo-Ruiz et al., 2015). This effective field capacity was calculated and defined by ASAE (2005). Due to higher crop evapotranspiration (ET_c) demands for the dense canopies and the low relative soil volume available for each tree, more irrigation water ha^{-1} is necessary for super high-density olive orchards.

The Mediterranean olive growing area is characterized by water deficits during summer (Cabezas et al., 2020). Available water resources

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are often insufficient to satisfy olive irrigation demands; thus, it is necessary to reduce the amount of water applied. Two of the most widely assessed strategies to save water are Continuous Deficit Irrigation (CDI), in which only a percentage of ET_c is applied during the all-vegetative period (Martín-Vertedor et al., 2011; Patumi et al., 1999) and Regulated Deficit Irrigation (RDI), which consists of irrigating below ET_c only during plant water-stress periods that can be tolerated (Gómez-del-Campo, 2013). Other strategies can be found in (Steduto et al., 2012). An adequate water deficit management can lead to increase irrigation Water Productivity (Arbizu-Milagro et al., 2022; Corell et al., 2019; Martínez-Gimeno et al., 2022; Moriana et al., 2003).

It is necessary to properly define periods of water stress which can be tolerated and the level of irrigation reduction because water scarcity at certain phenological growth stages can negatively affect vegetative development and yield. For example, in olives, a moderate water deficit after pit hardening does not seem to affect fruit growth compared to trees without water deficit (Rosecrance et al., 2015); however, water stress in the final moments of olive growth can cause a reduction in fruit diameter and oil yield. It seems that negative effects are minimized between pit hardening and the onset of fruit ripening (Alegre et al., 2002; Iniesta et al., 2009; Tognetti et al., 2006; Tovar et al., 2002). On the contrary, certain phenological growth stages are particularly sensitive to water-stress conditions, which are common in the Mediterranean climate. For example, the stem elongation period is very sensitive to low soil moisture, especially in dry, warm weather leading to fruit drop, fruit size reduction, and alternate bearing. (Girona et al., 2004; Rapoport et al., 2012).

The two irrigation strategies –RDI (75% of ET_c; without irrigation in summer) and CDI (75% of ET_c)– along with the application of 100% ET_c (Control) were compared and found to produce similar yields in both treatments (Moriana et al., 2003). Other experiments were carried out to study the CDI strategy (Patumi et al., 1999) and RDI during the pit hardening phenological stage (Alegre et al., 2002; Goldhamer, 1999; Motilva et al., 2000; Tovar et al., 2002). These studies found no differences in terms of olive production between the control and the two deficit irrigation strategies. On the contrary, more recent studies have indicated that the RDI strategy obtained greater water savings and greater water productivity compared to the CDI strategy (Siakou et al., 2021). However, trees under the CDI strategy had lower transpiration rates than fully irrigated trees (López-Bernal et al., 2018).

Moreover, the irrigation strategy can influence the olive fruit composition and the corresponding oil quality. Some studies have concluded that early water stress produces an increase in the phenolic concentration of olive oil compared with full irrigation (Gucci et al., 2019). Similar results have been reported for RDI treatments during pit hardening (García-Garví et al., 2022; Sánchez-Rodríguez et al., 2020). However, a late deficit during the oil synthesis period causes the opposite effect, decreasing the phenol content as well as other qualitative components of the oil (García et al., 2020).

The objective of this study was to assess the effects of distinct deficit irrigation strategies on growth and production components in young, super high-density, olive groves. The assessment will provide irrigation management strategies that could reduce water consumption without reducing production parameters while maintaining controlled vegetative development.

2. Materials and methods

2.1. Site description

The experiment was conducted during three consecutive growing seasons from April to December at a commercial orchard planted with *cv.* "Arbequina i-18" (*Olea europaea* L.) located in the northeast of Spain (42º 14 57.73" N; 2º 2 58.45" W). Trees were 4-year-old at the beginning of the experiment and were hedgerow trained with a 4 m x 1.5 m spacing so they could be harvested using a straddle canopy shaker. The orchard harvest date was decided by the commercial plot technician to maximize oil yield on a dry basis and attend to the harvester's availability. Soil was relatively deep (> 1.5 m), with a loam-clay-sandy texture, alkaline pH, low organic matter, and high calcium carbonate content. Field capacity was 29%, permanent wilting point was 9%, bulk density varied from 1.44 to 1.52 t $m^{-3,}$ and hydraulic conductivity was 3.9 and 1.6 cm•h^{-1} at 30 and 60 cm depths, respectively. Apart from the high clay content and high bulk density, the main limitation of the soil was salinity, which could reach 1.6 dS m^{-1} in the soil and 1.1 dS m^{-1} in the irrigation water. Orchard management for all treatments was uniform, except for irrigation.

The orchard was located in a continental Mediterranean climate (Fig. 1), therefore, irrigation was advisable. The commercial orchard irrigation system included an automatic irrigation controller and a general flowmeter. The flowmeter controlled the irrigation flow in the area where the experimental plots were located. Drip irrigation was carried out during the irrigation season each year using one dripline per tree row with integrated-drippers 0.6 m apart and 2.5 l•h^{-1} per dripper. Each dripline was controlled by a manual valve, which was partially closed to adjust the desired flow in each treatment. The partial closure of the manual valves was adjusted every year before starting irrigation and each emitter flow was measured to adjust for each treatment. Thus, the irrigation time was set and maintained the same for all treatments by the automatic irrigation controller. Dripline valves for the Precision strategy were closed and opened manually according to dendrometer measurements during July and August. Meteorological data was obtained from an automatic weather station located in the orchard.

2.2. Experimental design and irrigation treatments

The experimental design was a randomized complete block with 5 treatments of irrigation and 3 replications each (15 experimental plots). Each replication composed of 7 trees located in a single row with two adjacent buffer rows. Moreover, all measurements were taken from the five central trees.

All irrigation strategies were designed based on the daily crop ET_c calculated using the Penman-Monteith-FAO method (Allen et al., 1998) using data from the automatic weather station [Eq. 1]. As we have a perennial leaf crop (Girona i Gomis, 1996), the constant crop coefficient of 0.7 (K_c) was used for this high-density crop in full production which was within the wide range (0.5 – 0.75) considered by other authors (Connor et al., 2014). A tree ground cover coefficient of 0.75 (K_r) (Fereres and Castel, 1981). Canopy cover was measured in the first year of the tests Sc = 37.5%) and the same value was applied for the three years of study because the trees were not pruned during this period and the main development was in height. Thus, canopy cover hardly varied through the experimental period and Kr was considered constant [Eq. 2].

$$ETc = ET_0 \times Kc \times Kr \quad (1)$$

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

All irrigation strategies, except continuous deficit irrigation (CDI), received full water needs from April to June constituting no differences with the fully irrigated control treatment. The irrigation was carried out to obtain an adequate flowering set, fruit setting, and more shoots for the following year. This water status was maintained until the pit hardening phenological stage, which took place in early July. From pit hardening to the beginning of fruit ripening (early September), sensitivity to water deficit was considered to be less important. This effect is due to stomata closing caused by a high daily Vapor Pressure Deficit (VPD). Hence, vegetative growth stopped during the summer and irrigations were limited to those that maintained the photosynthetic functions of the leaves. From September to October (the fruit ripening and oil accumulation period) water stress sensitivity reached maximum again, therefore, all strategies except CDI received full water needs again until

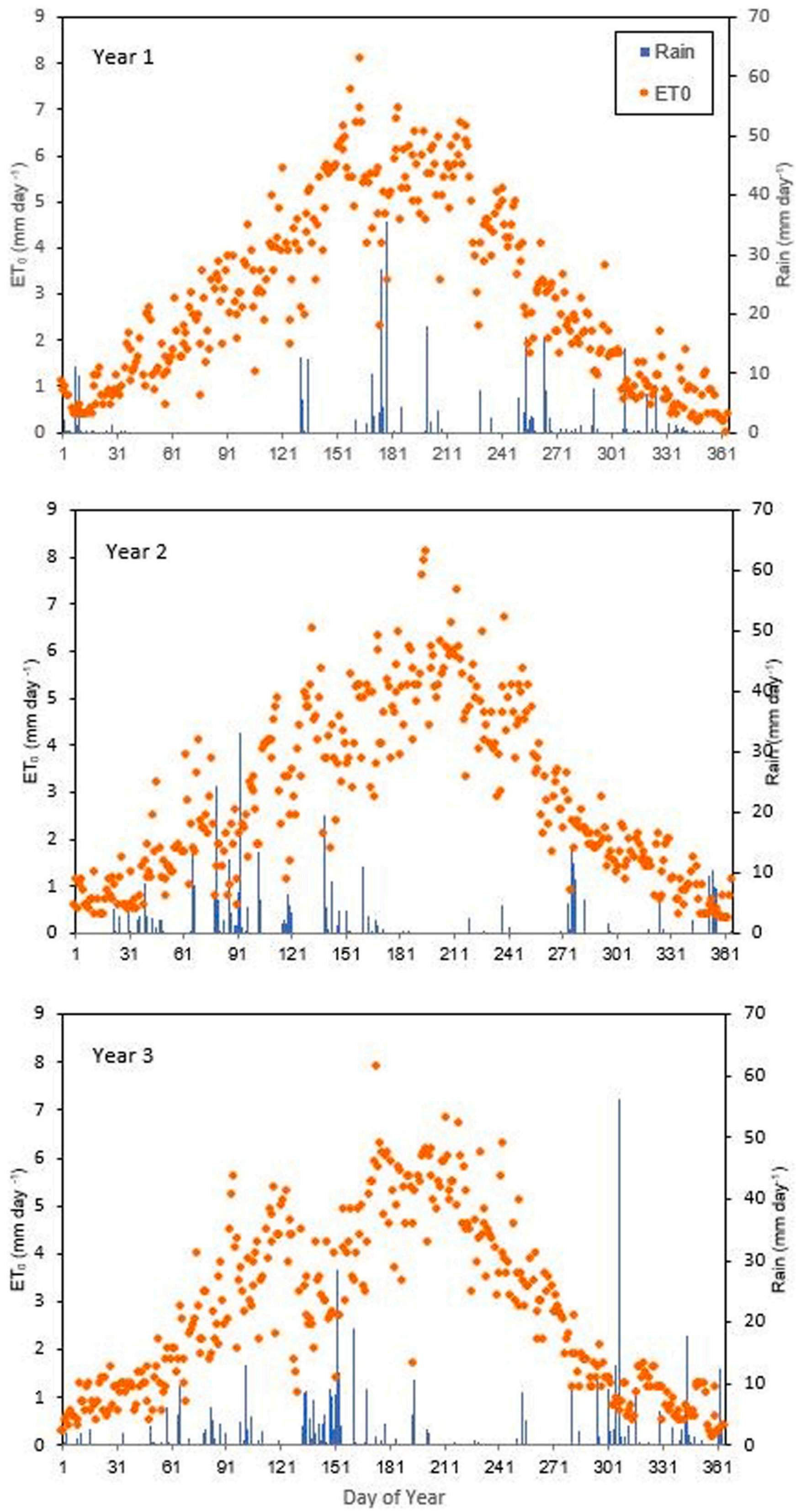

Fig. 1. Potential evapotranspiration (ET0) and rainfall registered by the automatic weather station located in the tested orchard.

harvest which took place during November in the three tested years.

Considering these premises, irrigation strategies were defined as follows:

- Control: 100% ET_c during the whole irrigation season.
- Moderate regulated deficit irrigation (MRDI): The same as the control except in July and August (summer vegetative growth stop) irrigation was 50% ET_c
- Severe regulated deficit irrigation (SRDI): The same as the control except in July and August (summer vegetative growth stop) irrigation was 25% ET_c
- Continuous deficit irrigation (CDI): 50% ET_c the whole irrigation season (From April to early November)
- Databased precision irrigation (Precision): The same as the control except in July and August (summer vegetative growth stop), irrigation only took place after two consecutive days of decreased trunk diameter according to dendrometer data (Verdtech dendrometer, Verdesmart CO S.L., Spain). Water applied in each irrigation during this period was equivalent to the ET_c of the previous day. The dendrometer was installed 15 cm above the ground on the main trunk of a representative tree for the Precision strategy. The dendrometer took and sent measurements every 15 min via radio to a data logger. The daily trunk growth was calculated from the daily curves as the difference between two maximum trunk diameters of two consecutive days. In the Precision strategy, dripline valves were manually opened when the dendrometer provided two consecutive days of trunk diameter decrease compared to the previous day.

2.3. Vegetative measurements

In each replication, tree height from the soil, the length of two lateral bearing branches, and trunk diameters were measured at 15 cm above the soil. The measured branches were randomly selected each year at eye height and distributed around the canopy boundary. A total of 15 trunk diameters, tree heights, and 30 lateral bearing branch lengths were measured. Measurements were taken at the 5 different phenological stages as follows: 15 days after stem elongation (I), pre-flowering (II), 5 weeks after fruit setting (III), beginning of fruit ripening (IV) and pre-harvesting (V) (Table 1).

The variations in annual growth were studied by comparing the calculated trunk cross-sectional area (TCA, in cm^2) at the end of the two consecutive irrigation seasons (early November, just before harvest), and by obtaining the Trunk Cross-sectional Area Increase (TCAI, $cm^2 \cdot year^{-1}$) [Eq. 1].

$$TCAI \quad \left(cm^2 \bullet year^{-1}\right) = \frac{TCA_i - TCA_{i-1}}{1year} \tag{3}$$

2.4. Production measurements

During the month before harvest, a random sample of 100 fruit from around the canopy boundary at eye height was taken from 5 trees per replication. Average fruit weight, Maturity Index (MI) based on the assessment of skin and pulp color, on a scale ranging from 0 (100% deep green skin, fruit hard) to 7 (100% purple flesh and black skin) (Berenguer et al., 2006) were measured throughout the month prior to harvest. The maturity index (MI) is defined as follows:

$$MI = \frac{(n_0 \times 0) + (n_1 \times 1) + (n_2 \times 2) + (n_3 \times 3) + (n_4 \times 4) + (n_5 \times 5) + (n_6 \times 6) + (n_7 \times 7)}{100} \tag{4}$$

where n indicates the number of olives at each maturity stage ($n_0 - n_7$). (Berenguer et al., 2006). Fruit water content and fat content by the Soxlhlet method were measured. On the harvest date, the three central trees of each replication were manually harvested to determine fruit yield, calculated as average production per tree (Frías et al., 1999). Yield efficiency (YE, $kg \bullet cm^{-2}$) was calculated as the production of a tree in relation to the trunk cross-sectional area (TCA, cm^2) to consider the differences in the size of the tree and its growth at the time of harvest (Caruso et al., 2013). The resource distribution ($kg \bullet cm^{-2} \bullet year^{-1}$) was also estimated as a ratio between the olive yield and the trunk cross-sectional area increase (TCAI) (Ebel et al., 1995; Martínez-Gimeno et al., 2022).). Furthermore, oil yield per tree was calculated after measuring the oil content extracted from a fruit sample using an Abencor laboratory assembly (Frías et al., 1999). Oil yield efficiency (OYE) was calculated as the oil production of a tree in relation to the TCA (Caruso et al., 2013).

2.5. Data analysis

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

3. Results

3.1. Water saving

Meteorological data, ET_0, and rainfall were measured showing typical Mediterranean values. Most of the rain fell before the beginning of the irrigation season and during the first and third irrigation periods. During the second irrigation period (July and August) rain was scarce (Fig. 2, Table 2).

Table 1
Irrigation periods considered in relation to the phenological stage of the olive tree.

Irrigation period	Start	Finish	Phenological stage	Irrigation	Measurements related to phenological phase
Period 0	1st January	30th March	Winter dormancy Pre-budding	No	
Period 1	1st April	30th June	Budding, flowering and fruit setting	Yes	Phase I:15 days after budding Phase II: Pre-flowering
Period 2	1st July	31st August	Pit hardening	Yes	Phase III: 5 weeks after fruit setting
Period 3	1st September	31st October	Fruit growth and ripening	Yes	Phase IV: beginning of fruit ripening Phase V: Pre-harvesting
Period 4	1st November	31st December	Harvesting. Winter dormancy	No	

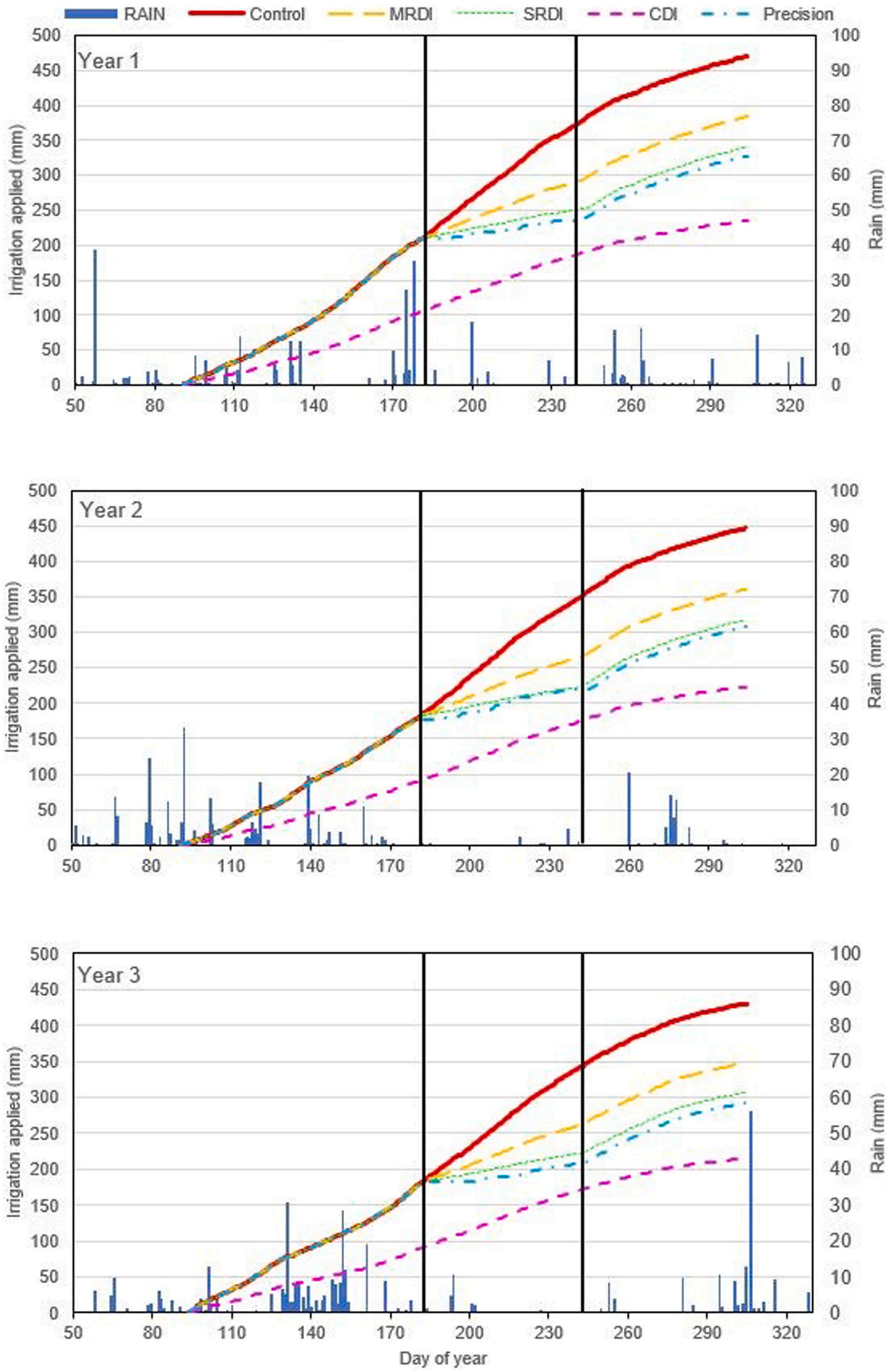

Fig. 2. Water applied and distribution of rain (vertical bars) during the irrigation season in the three years of the experiment. Vertical lines indicate the beginning and end of the summer vegetative growth stop.

Every year, the amount of irrigation water applied varied, but the differences between irrigation strategies were maintained relatively constant (Table 2). Except for the CDI strategy, all other strategies only restricted water applied during summer, so the irrigation data are presented in three periods: before the summer vegetative stop (Period I), during the summer vegetative stop (Period II), and after the summer vegetative stop (Period III). During period II (July and August), trunk diameter data were used to support irrigation decisions in the Precision strategy, reducing the number of irrigation events compared with the rest of the treatments in which the irrigation was carried out daily. In this strategy, the number of irrigations during the summer vegetative stop, period II, was reduced to 12 for years 1 and 3, and to 16 in year 2, which was drier than the other years. Thus, in the Precision strategy, the water applied in period II was reduced to 83%, 77%, and 84% of that applied in the control strategy for each year of the experiment, respectively. For each year of the experiment, all irrigation strategies achieved significant water savings compared to the control strategy. Greater water savings were provided by the CDI strategy (50%) followed by

Table 2
Olive seasonal evapotranspiration (ETc), rain, and water distribution applied during the different experiment's irrigation seasons are presented in three periods: Period 0: No irrigation, winter dormancy (January – March) Period 1: Irrigation during budding, flowering and fruit setting (April-June); Period 2: irrigation during pit hardening (July and August); Period 3: irrigation during fruit growth and ripening. (September-October); Period 4: No irrigation, winter dormancy. Total water saving for each treatment compared to Control strategy is indicated as a percentage.

		Irrigation (mm)						
Year	Irrigation period	Control	MRDI	SRDI	CDI	Precision	ET_c	**Rain**
	Period 0	-	-	-	-	-	73	90
1	Period 1	210	210	210	106	210	212	175
	Period 2	172	86	43	85	29	172	39
	Period 3	88	88	88	44	88	85	73
	Period 4	-	-	-	-	-	27	40
	Total	**470**	**384**	**341**	**235**	**327**	**569**	**417**
	Water saving (%)	**0**	**18**	**27**	**50**	**30**		
	Period 0	-	-	-	-	-	67	131
2	Period 1	175	175	175	88	175	179	171
	Period 2	182	97	54	90	42	182	10
	Period 3	89	89	89	45	89	86	70
	Period 4	-	-	-	-	-	36	48
	Total	**446**	**361**	**318**	**223**	**306**	**540**	**430**
	Water saving (%)	**0**	**19**	**29**	**50**	**31**		
	Period 0	-	-	-	-	-	71	64
3	Period 1	182	182	182	91	182	184	234
	Period 2	164	82	41	82	27	164	24
	Period 3	84	84	84	42	84	80	54
	Period 4	-	-	-	-	-	29	136
	Total	**430**	**348**	**307**	**215**	**293**	**528**	**512**
	Water saving (%)	**0**	**19**	**29**	**50**	**32**		

Precision irrigation along with SDRI (31% and 28% respectively) and finally MRDI (19%).

3.2. Vegetative response

Regardless of the irrigation strategy, tree height increased rapidly during phenological stages I to III. Between phases, III and IV (pit hardening), growth stopped and, at the end of the summer, there was a second vegetative growth increase. The vegetative stop was affected by water management, which provoked a lower level of growth in the CDI, SRDI, and MRDI strategies (Supplementary Material Fig. S.1). MRDI and SRDI height decrease was due to apical buds withering because of the lack of water and soil conditions. This fact resulted in a mean tree height reduction in this treatment (Table 3). Once the full irrigation was recovered, the highest shoot without apical damage resumed its growth and was taken as the final tree height. Tree height for the control strategy showed higher values than the other strategies, especially since the second year of the study, where the decrease in tree height during phases III and IV did not recover in phase V of the same year for RDI and CDI strategies. In the CDI strategy, tree height was affected throughout the whole irrigation season, so it increased slower from the beginning of the experiment, and the effect during the pit hardening period was lighter than the rest of the irrigation strategies. The Precision strategy showed greater growth capacity after the vegetative stop period than the rest of the strategies; it was similar to the control.

Lateral bearing branch growth followed a similar pattern to tree height growth (Shown in Supplementary Material Fig. S.2). Branches rapidly grew during phases I to III and suffered a growth stop or even a length decrease due to apical buds withering in phases III to IV. When the pit hardening period ended and irrigation was reestablished, most of the irrigation strategies recovered and achieved a similar growth rate as the control strategy; excluding SRDI and CDI. The CDI strategy provided between 50% and 65% less absolute lateral branch growth than the control strategy (Table 3).

Despite differences in tree height and lateral branch growth rate, trunk diameter increase throughout the irrigation period provided less evident differences between irrigation strategies. Trunk diameter growth stop from phase III to IV was pronounced in CDI and RDI strategies and particularly in the SRDI irrigation strategy for the three years (Shown in Supplementary Material Fig. S.3). After this period of deficit

Table 3
Absolute tree height growth (cm) and lateral branches growth (cm) for each year, measured from April to November. Different letters showed significant differences ($p \leq 0.05$) among treatments for the same year according to Duncan's test.

Absolute tree height growth (cm)			
Strategy	**Year 1**	**Year 2**	**Year 3**
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[a]
SRDI	15.0 ± 3.5 ab	-3.3 ± 3.2c[a]	-3.0 ± 1.2 d[a]
CDI	6.0 ± 1.5 b	5.7 ± 0.7 ab	3.3 ± 2.4 bc
Precision	19.3 ± 2.9 a	0.3 ± 0.7 bc	7.0 ± 1.5 ab
Lateral branches growth (cm)			
Strategy	**Year 1**	**Year 2**	**Year 3**
Control	21.0 ± 1.0 a	20.3 ± 4.9 a	13.3 ± 0.7 a
MRDI	18.3 ± 0.7 ab	15.0 ± 2.6 ab	11.7 ± 0.7 a
SRDI	15.7 ± 3.8 b	14.7 ± 2.4 ab	4.3 ± 0.7 b
CDI	9.7 ± 0.9c	7.0 ± 1.5 b	6.7 ± 0.9 b
Precision	17.0 ± 1.5 ab	13.7 ± 2.6 ab	14.0 ± 1.5 a

[a] Negative data means that some apical buds were dried out, resulting in a lower average height at the measurement moment than the beginning.

Table 4
Trunk cross-sectional area increase (TCAI, $cm^2 \cdot year^{-1}$) measured each year from April to November. According to Duncan's test, different letters showed significant differences ($p \leq 0.05$) among treatments for the same year.

Strategy	TCAI ($cm^{-2} \cdot year^{-1}$) Year 1	Year 2	Year 3	Cumulative
Control	1.8 ± 0.3 a	2.8 ± 0.9 ab	2.1 ± 0.9 a	6.6 ± 0.8 a
MRDI	1.8 ± 0.8 a	3.6 ± 0.3 a	1.2 ± 0.5 a	6.6 ± 0.2 a
SRDI	1.7 ± 0.3 a	3.5 ± 0.4 a	0.9 ± 0.3 a	6.1 ± 0.9 a
CDI	1.1 ± 0.2 a	1.2 ± 0.2 b	0.5 ± 0.1 a	2.9 ± 0.5 b
Precision	2.0 ± 0.3 a	3.9 ± 0.2 a	1.0 ± 0.2 a	6.8 ± 0.6 a

Table 5
Cumulative tree height and trunk diameter growth from April year 1 to November year 3 and average lateral branches growth from April to November. Different letters showed significant differences ($p \leq 0.05$) among treatments for the same measure according to Duncan's test.

Strategy	Cumulative growth: Tree height (cm)	Trunk diameter (mm)	Average growth: Lateral branches (cm)
Control	41.7 ± 6.2 a	12.4 ± 1.6 a	18.2 ± 1.6 a
MRDI	29.0 ± 1.0 ab	12.9 ± 0.6 a	15 ± 0.9 ab
SRDI	12.0 ± 3.8c	11.9 ± 1.5 a	11.6 ± 1.9 bc
CDI	19.0 ± 5.5 bc	6.0 ± 1.1 b	7.8 ± 0.6c
Precision	29.3 ± 3.5 ab	12.9 ± 1.0 a	14.9 ± 1.4 ab

irrigation, once irrigation was reestablished, trees showed a high recovery capacity. All strategies, except for the CDI strategy, achieved similar trunk diameter growth to the control. In the CDI strategy, the first season growth was less, resulting in a smaller trunk diameter after three growing seasons of the experiment.

In general, trunk cross-sectional area increase (TCAI) was affected by alternate bearing, with greater growth observed in off-years (Year 2) compared to on-years (Years 1 and 3). These fluctuations of trunk growth according to production seemed to be greater when irrigation was closer to a fully irrigated treatment (Control, RDI, and Precision strategies); however, this relationship was less evident for trees under continous water deficit (CDI strategy). Despite this interaction between irrigation and production, TCAI barely showed significant differences between irrigation strategies (Table 4). Trunk growth was much more independent from irrigation than the absolute lateral branch or tree height growth (Table 5).

Only the CDI strategy had significantly lower trunk growth than the rest of the treatments, providing 56% less TCAI than the control strategy after the three years of the experiment. However, SRDI showed a growth similar to CDI in terms of tree height and lateral branches growth, being significantly lower than the control. Only the MRDI and Precision strategies did not significantly differ ($p \leq 0.05$) in any growth measurement from the control strategy (Table 5).

3.3. Production measurements

Irrigation strategies had a significant effect on the ripeness process during the month prior to harvesting (Fig. 3). The Maturity Index (MI) evolved distinctly between the most stressful irrigation treatments and the control strategy. The most severe deficit irrigation strategies, CDI and SRDI, had a quick MI increase like MRDI, while the control fruit ripened much slower. Finally, the Precision strategy gave intermediate MI values. It was similar to the control strategy during the two first weeks and similar to other strategies in the last two weeks (Fig. 3).

At harvest, all strategies showed a significantly higher MI than the control and the Precision strategies, except for the first year. The fact that ripening was advanced in deficit strategies should be considered to determine the optimum harvest date considering that irrigation increased fruit water content while water stress increased fat content (Table 6).

At harvest, the lowest fruit water content was found in the most stressful strategies (CDI and SRDI); even MRDI showed significant differences ($p \leq 0.05$) compared to the control and the Precision strategy (Table 6), which produced similar values in the three years studied. The harvest was carried out the first week of November. Olive yield was significantly ($p \leq 0.05$) higher in the less stressed strategies, which were the control, Precision, and MRDI strategies (Table 6). Olive yield after three years was 30% and 28% less than the control in CDI and SRDI strategies, respectively, and only 6.5% less in the MRDI strategy. Assessing olive yield components, the number of fruit per tree did not show significant differences ($p \leq 0.05$) between strategies. Only in the third year, the number of fruit in the CDI strategy was significantly lower ($p \leq 0.05$) compared to the other strategies. However, fresh fruit weight provided significantly lower values in the SRDI and CDI strategies. Thus, fresh fruit weight was the main yield component that explained olive yield differences. Finally, oil yield followed a similar pattern to olive yield (Table 6).

Yield efficiency (YE) presented differences as the experiment advanced; with significant differences ($p \leq 0.05$) only for the second and third years between SRDI and the rest of the strategies (Table 7). In the second year, which was an off year due to alternate bearing, YE decreased for all strategies. However, only the SRDI strategy showed significant differences ($p \leq 0.05$). Oil Yield Efficiency (OYE) showed similar behavior, but it did not provide significant differences ($p \leq 0.05$) until the last year when the Precision, CDI, and SRDI strategies stood out with a higher OYE than the other irrigation strategies. Furthermore, resource distribution provided significant differences only during the second year, which was an off year. The CDI treatment reached the highest level, which meant that trees prioritize fruit production over tree growth and this effect is more evident in on years.

4. Discussion

Tree growth was affected by water management strategy; mainly seen in tree height and lateral branch growth (Tables 3 and 5 and Supplementary Material). Negative growths could be measured due to apical bud withering, pests or diseases, or due to mechanical damage during harvesting (Pérez-Ruiz et al., 2018). If the irrigation strategy was adequate, shoot growth could overcome these setbacks, otherwise, shoot growth could be negative, even for several measurements. However, trunk diameter and TCAI showed a slower response, providing significant results ($p \leq 0.05$) in off years or at the end of the experiment in the CDI strategy (Table 4).

The effect of the irrigation strategies on height and lateral branch growth during the pit hardening phase was greater in CDI and SRDI treatments and lower in the Precision and control strategies, especially in the on years (See Supplementary Material Figs. S.1 and S.2). Furthermore, the CDI strategy showed a significant decrease for height, lateral branches growth, and trunk diameter compared to control from the first year (Supplementary Material and Table 3) according to results reported by Moriana et al. (2003), Grattan et al. (2006), Iniesta et al. (2009), and Pierantozzi et al. (2014). This seems to indicate that constant water deficit reduces growth; which could be interesting to control vigor in super high-density olive orchards (Martínez-Gimeno et al., 2022; Tognetti et al., 2006). This objective should be achieved without compromising olive oil yield and economic profit. This can be accomplished through a regulated deficit strategy that applies approximately 60% of the crop's water needs when water availability is limited, as suggested by Fernández et al. (2020). These water-saving measures align with the 31% reduction in water consumption observed in our study. Nevertheless, oil quality is conditioned for both irrigation amount and fruit bruising during harvesting (Dag et al., 2008) along with fruit location within the olive canopy (Castillo-Ruiz et al., 2015). Complementary measures to control olive vigor in super high-density olive

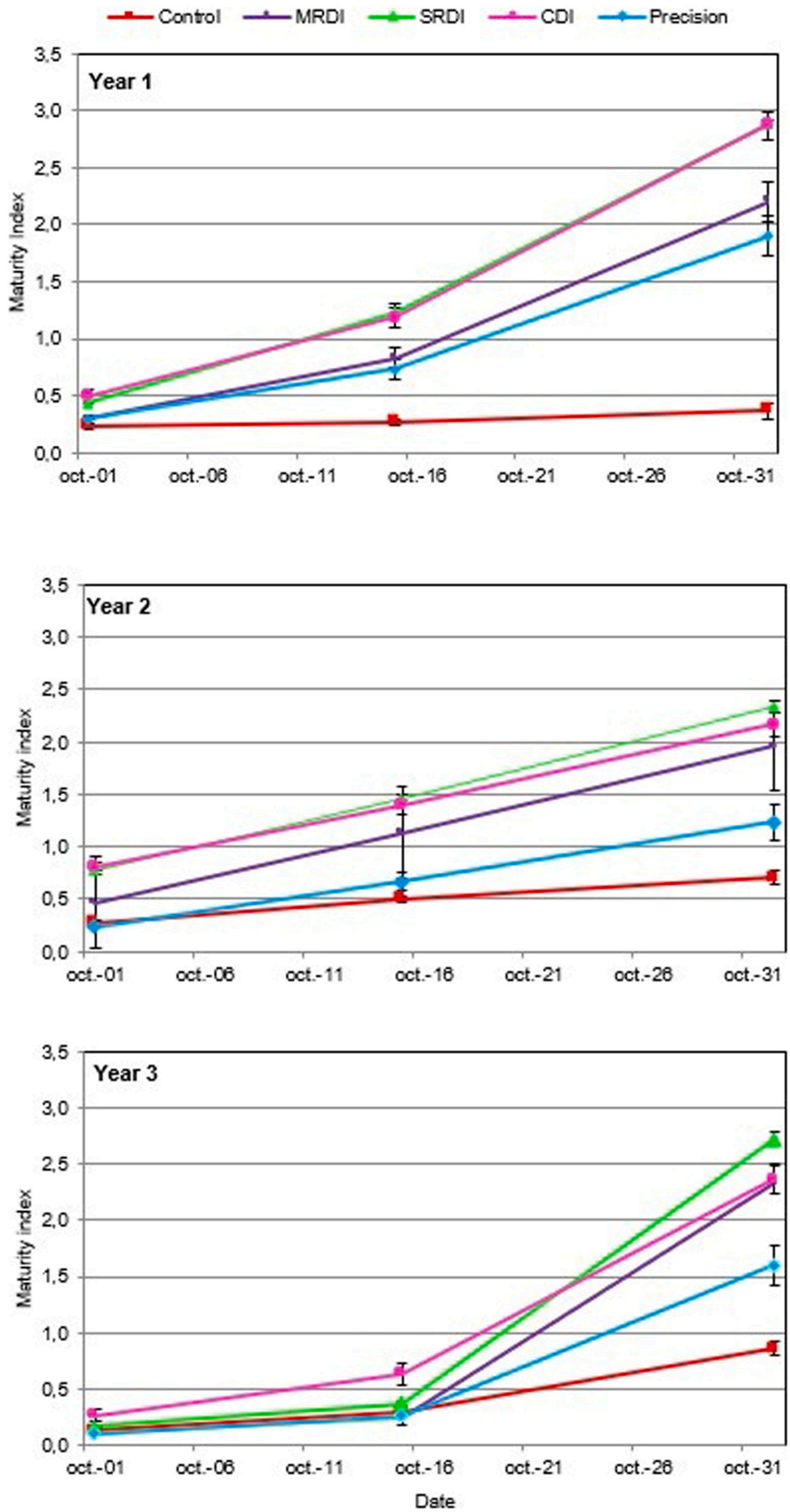

Fig. 3. Maturity Index evolution throughout the month of October prior to the harvest in the three years of experience. The vertical segments represent the typical error.

Table 6

Olive yield (OY, kg tree^{-1}) and oil yield (Oil Y, kg tree^{-1}), yield components: Fresh fruit weight (FFC, g), fruit number (FN, fruit tree^{-1}), fruit water content (FWC, %), fat content (FC, % DW), and Maturity Index (MI) of young olive trees (cv. Arbequina) during the three years of the experiment for the 5 irrigation strategies studied. According to Duncan's test, different letters showed significant differences ($p \leq 0.05$) among treatments for the same year.

	Year 1	Year 2	Year 3	
OY				**Cumulative**
Control	3.37 ± 0.11 a	2.84 ± 0.02 a	4.15 ± 0.13 a	10.36 ± 0.1 a
MRDI	3.2 ± 0.1 a	2.8 ± 0.15 a	3.69 ± 0.18 b	9.68 ± 0.36 b
SRDI	2.51 ± 0.05 b	1.98 ± 0.05 b	2.96 ± 0.06c	7.46 ± 0.06c
CDI	2.59 ± 0.05 b	1.95 ± 0.07 b	2.74 ± 0.08c	7.28 ± 0.17c
Precision	3.33 ± 0.14 a	2.87 ± 0.06 a	4.22 ± 0.04 a	10.41 ± 0.1 a
FFW				**Average**
Control	1.98 ± 0.05 a	2.15 ± 0.06 a	1.9 ± 0.05 a	2.01 ± 0.06 a
MRDI	1.93 ± 0.08 a	2.13 ± 0.09 a	1.85 ± 0.08 a	1.97 ± 0.09 a
SRDI	1.62 ± 0.06 b	1.76 ± 0.07 b	1.56 ± 0.05 b	1.65 ± 0.06 b
CDI	1.63 ± 0.08 b	1.77 ± 0.08 b	1.56 ± 0.07 b	1.65 ± 0.07 b
Precision	1.99 ± 0.11 a	2.17 ± 0.12 a	1.91 ± 0.11 a	2.02 ± 0.12 a
FN				**Cumulative**
Control	1707 ± 104 a	1328 ± 30 a	2191 ± 70 a	5226 ± 169 a
MRDI	1664 ± 117 a	1322 ± 128 a	2000 ± 139 ab	4986 ± 368 a
SRDI	1553 ± 72 a	1131 ± 39 a	1909 ± 99 ab	4592 ± 199 a
CDI	1596 ± 50 a	1101 ± 40 a	1760 ± 35 b	4457 ± 101 a
Precision	1684 ± 140 a	1335 ± 95 a	2222 ± 114 a	5241 ± 332 a
FWC				**Average**
Control	45.4 ± 0.43 a	46.6 ± 0.19 a	47.5 ± 0.43 a	46.5 ± 0.34 a
MRDI	42 ± 0.59 b	44.4 ± 0.47 bc	45.1 ± 0.57 b	43.8 ± 0.53 b
SRDI	42.3 ± 0.79 b	44 ± 0.84c	45 ± 0.81 b	43.8 ± 0.8 b
CDI	40.4 ± 0.38c	42.7 ± 0.55c	43.5 ± 0.4 b	42.2 ± 0.43 b
Precision	44.2 ± 0.26 a	46 ± 0.26 ab	47.2 ± 0.26 a	45.8 ± 0.26 a
FC				**Average**
Control	53.4 ± 0.53 bc	54.7 ± 0.53 bc	55.4 ± 0.53 bc	54.5 ± 0.53 bc
MRDI	50.83 ± 0.86c	52.13 ± 0.86c	52.83 ± 0.86c	51.93 ± 0.86c
SRDI	56.23 ± 0.49 ab	57.53 ± 0.49 ab	58.23 ± 0.49 ab	57.33 ± 0.49 ab
CDI	57.27 ± 0.32 a	58.57 ± 0.32 a	59.27 ± 0.32 a	58.37 ± 0.32 a
Precision	52.53 ± 1.95c	53.83 ± 1.95c	54.53 ± 1.95c	53.63 ± 1.95c
Oil Y				**Cumulative**
Control	0.72 ± 0.03 a	0.64 ± 0.01 a	0.86 ± 0.03 ab	2.23 ± 0.02 ab
MRDI	0.65 ± 0.01 ab	0.62 ± 0.04 ab	0.9 ± 0.05 a	2.17 ± 0.07 b
SRDI	0.58 ± 0.01 b	0.53 ± 0.01 b	0.76 ± 0.03 bc	1.87 ± 0.04c
CDI	0.61 ± 0.01 b	0.55 ± 0.03 b	0.7 ± 0.01c	1.86 ± 0.05c
Precision	0.72 ± 0.04 a	0.69 ± 0.04 a	0.97 ± 0.05 a	2.38 ± 0.07 a
MI				**Average**
Control	0.4 ± 0.1c	0.7 ± 0.12c	0.9 ± 0.07 d	0.6 ± 0.07 d
MRDI	2.2 ± 0.1 b	2 ± 0.09 a	2.3 ± 0.09 b	2.2 ± 0.07 b
SRDI	2.9 ± 0.2 a	2.3 ± 0.09 a	2.7 ± 0.03 a	2.6 ± 0.03 a
CDI	2.9 ± 0.1 a	2.2 ± 0.15 a	2.4 ± 0.12 b	2.5 ± 0.07 a
Precision	1.9 ± 0.2 b	1.2 ± 0.18 b	1.6 ± 0.06c	1.6 ± 0.09c

orchards could consist of the use of low-vigor varieties (Camposeo et al., 2021) or dwarfing rootstocks (Torres-Sánchez et al., 2022). The SRDI strategy also showed the lowest tree height growth since the second year and the lowest lateral branch growth in the third year (Table 3). These results are consistent with those reported by Melgar et al. (2008).

The CDI irrigation strategy showed significantly lower TCAI and trunk diameter regarding cumulative values (Tables 4 and 5), according to previous research, which found that trunk growth was not affected by controlled deficit irrigation (Moriana et al., 2003) because when irrigation was reestablished, a high recovery capacity was recorded as described for vegetative and productive response in off years (Palese et al., 2010). However, the CDI strategy provided the lowest trunk diameter, from the second year, pit hardening phase onwards (Supplementary Material Fig. S.3).

Olive yield was affected by the amount of irrigation water applied, except for the Precision strategy, which produced the highest cumulative olive yield while achieving more than 30% of the yearly water savings compared to the control strategy. The cumulative olive yield was significantly ($p \leq 0.05$) lower in the MRDI, SRDI, and CDI strategies with respect to the control of 7%, 28%, and 30% (Table 6) achieving water savings of 19%, 28%, and 50% (Table 2) respectively. Similar results were obtained by Ben-Gal et al., 2021. These differences in olive yield were mainly due to fruit weight and greater water content (Martínez-Gimeno et al., 2022; Moriana et al., 2003), while fat content lessened the differences as it was higher for less irrigated strategies than for the control, MRDI and Precision strategies (Table 6). However, fat content could not compensate olive yield, as a result, oil yield values remained significantly higher ($p \leq 0.05$) for the Precision and control strategies than for the SRDI and CDI. Furthermore, the distinct irrigation strategies affected oil yield less than olive yield; oil yield cumulative values constituted 3%, 16%, and 17% reductions for MRDI, SRDI, and CDI respectively, compared to the control strategy as described by Martínez-Gimeno et al. (2022). These results could be explained not only by the fact that a higher moisture content in the fruit negatively affected the industrial extractability (Berenguer et al., 2006), but also because the oil content increased as the water stress rose, especially in the treatments with greater water restrictions (SRDI and CDI).

The YE decreased from the second year onward with the applied water; but, only with significant differences ($p \leq 0.05$) for SRDI (Table 7). So, the SRDI strategy gave YE values 32% and 21% lower than the control for the second and third years, respectively; which was similar to previous trials (Caruso et al., 2013; Martínez-Gimeno et al.,

Table 7
Yield efficiency (Yield TCA-1, in kg•cm-2), oil yield efficiency (Oil yield TCA-1, in g•cm-2) and resources distribution (kg•cm-2•year-1), for the three years of the experiment. According to Duncan's test, different letters showed significant differences ($p \leq 0.05$) among treatments for the same year.

	Yield efficiency (YE, kg•cm^{-2})			
	Year 1	**Year 2**	**Year 3**	
Control	0.457 ± 0.01 a	0.283 ± 0.02 a	0.337 ± 0.01 a	
MRDI	0.497 ± 0.08 a	0.273 ± 0.03 a	0.32 ± 0.02 a	
SRDI	0.37 ± 0.01 a	0.193 ± 0.01 b	0.267 ± 0.02 b	
CDI	0.403 ± 0.03 a	0.257 ± 0.02 ab	0.333 ± 0.01 a	
Precision	0.467 ± 0.02 a	0.263 ± 0.01 ab	0.353 ± 0.01 a	
	Oil Yield efficiency (OYE, g•cm^{-2})			
	Year 1	**Year 2**	**Year 3**	
Control	97.26 ± 2.58 a	63.93 ± 5.39 a	70.36 ± 1.44 b	
MRDI	101.3 ± 15.57 a	61.38 ± 8.09 a	68.92 ± 6.48 b	
SRDI	85.04 ± 2.93 a	51.72 ± 4.33 a	77.93 ± 4.4 ab	
CDI	95.43 ± 5.33 a	71.24 ± 4.49 a	85.44 ± 1.87 a	
Precision	100.91 ± 4.84 a	63.37 ± 5.58 a	81.05 ± 3.24 a	
	Resource distribution (kg• cm^{-2}•year^{-1})			
	Year 1	**Year 2**	**Year 3**	**Average**
Control	2.063 ± 0.46 a	1.233 ± 0.39 ab	2.783 ± 0.92 a	1.61 ± 0.22 b
MRDI	2.460 ± 0.94 a	0.790 ± 0.05 b	4.687 ± 2.3 a	1.46 ± 0.02 b
SRDI	1.547 ± 0.28 a	0.580 ± 0.08 b	4.190 ± 1.16 a	1.27 ± 0.18 b
CDI	2.530 ± 0.33 a	1.670 ± 0.30 a	5.200 ± 0.68 a	2.66 ± 0.36 a
Precision	1.790 ± 0.34 a	0.750 ± 0.04 b	4.660 ± 0.86 a	1.56 ± 0.15 b

2022). However, YE did not decrease in the CDI and Precision strategies as much as irrigation did, showing a greater yield efficiency than SRDI, with significant differences in the third year. Regarding the oil yield efficiency (OYE), all treatments showed behavior similar to the control during the first two years. However, OYE was significantly higher ($p \leq 0.05$) for the CDI and Precision strategies in the third year, which is consistent with the results reported by Caruso et al. (2013).

As mentioned above, the application of deficit irrigation influenced both, vegetative development and yield. However, it is possible to optimize oil production with considerable water savings while also regulating vegetative development (Martínez-Gimeno et al., 2022). This can be particularly interesting in super high-density crops where harvesting is performed using a straddle canopy shaker. Nevertheless, deficit irrigation with high water saving rates did not show a clear reduction in YE or OYE, although it could delay the first full harvest, as described by Caruso et al. (2013). Finally, the Precision strategy, which reduced irrigation only during period 2, the pit hardening phase (as shown in Tables 1 and 2), led to significant water savings of 31%, without compromising the yields of olive and oil.

5. Conclusions

Five irrigation strategies were evaluated in terms of water saving, vegetative growth, and production. This research demonstrated that olive tree irrigation can be optimized, as it is possible to reduce irrigation by 31% while preserving vegetative development, olive yield, and oil yield similar to the control. The Precision strategy did not show significant differences in tree height, lateral branches growth, trunk diameter growth, and olive and oil yields in all years, except for year 2, where there was a significant difference in tree height compared to the control. Furthermore, the Precision strategy provided the highest olive and oil yields, which were significantly greater than those obtained from SRDI and CDI strategies. However, it is worth noting that the Precision strategy exhibited lower maturity index values and higher fruit water content compared to the SRDI and CDI strategies. Similarly, the MRDI strategy could be of interest to achieve a 19% water savings compared to the control, with slight decreases in vegetative parameters but without affecting olive weight at harvest, or oil yield. However, the Precision strategy provided a significantly higher oil yield than MRDI.

On the other hand, the SRDI and CDI treatments resulted in reduced vegetative development, reflected in shorter tree height and decreased average lateral branch growth compared to control, and lower olive and oil productions.

Finally, both yield efficiency and oil yield efficiency were significantly higher for the Precision strategy in comparison with the control. However, the CDI strategy achieved the highest OYE because it prioritized fruit production over vegetative development, as indicated by the significantly greater resource distribution compared to any other strategy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108393.

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