



Article

Integrating Deficit Irrigation Strategies and Soil-Management Systems in Almond Orchards for Resilient Agriculture

Iván Francisco García-Tejero ^{1,*}, Juan Francisco Herencia-Galán ¹, Belén Cárcelos Rodríguez ², Abel Calderón-Pavón ¹, Javier Aldana Navarro ¹, Alfredo Emilio Rubio-Casal ³ and Víctor Hugo Durán Zuazo ²

¹ IFAPA Centro “Las Torres”, Carretera Sevilla-Cazalla km 12.2, 41200 Sevilla, Spain; juanf.herencia@juntadeandalucia.es (J.F.H.-G.); abel.calderon@juntadeandalucia.es (A.C.-P.); franciscoj.aldana@juntadeandalucia.es (J.A.N.)

² IFAPA Centro “Camino de Purchil”, Camino de Purchil s/n, 18004 Granada, Spain; belen.carcelos@juntadeandalucia.es (B.C.R.); victorh.duran@juntadeandalucia.es (V.H.D.Z.)

³ Department of Plant Biology and Ecology, University of Seville, Av. Reina Mercedes, s/n, 41012 Sevilla, Spain; aerubio@us.es

* Correspondence: ivanf.garcia@juntadeandalucia.es; Tel.: +34-955045500

Abstract: This work was conducted over three-year monitoring seasons of three almond cultivars (Guara, Marta, and Lauranne) subjected to deficit irrigation in combination with cover crops in a Mediterranean semiarid area (SW, Spain). Four water–soil treatments were evaluated based on the conjunction of two irrigation strategies: fully irrigated (FI), covering 100% of the ET_C , and regulated deficit irrigation (RDI), with two soil-management systems: bare soil (BS) and cover crop based on a mixture of vetch (*Vicia sativa* L.) and oat (*Avena sativa* L.) (CC). Throughout the study period in trees, the yield, the stem water potential (Ψ_{stem}), leaf nutrient content (N, P, K, Ca, Mg, Na, Fe, Zn, Mn, and Cu) in soils, organic carbon, microbial biomass, fluoresceine diacetate, and enzymatic activities (dehydrogenase, protease, β -glucosidase, and alkaline phosphatase) were determined. In addition, the dry matter and carbon fixation by plant covers were evaluated. For Guara and Lauranne, yield reductions (22 and 26%, respectively) were found for water-stressed (RDI-CC) plots with respect to non-stressed combination (FI-CC) plots, contrasting with cv. Marta, without a significant impact on productivity in all combinations. That is, the RDI ($\sim 3.000 \text{ m}^3 \text{ ha}^{-1}$) strategy enabled acceptable productivity, offering promising possibilities for cultivation performance under water-scarcity scenarios. Important differences in Ψ_{stem} could be observed and ascribed to irrigation strategies, especially for Guara and Lauranne, but without significant effects due to the soil-management systems applied. No differences were observed in the tree nutritional status due to the presence or absence of CC; however, its presence increased the fixation of atmospheric carbon, which was not the case under BS conditions. Additionally, CC significantly fostered the microbial processes and enzymatic activities, particularly in upper soil layers (0–10 cm) and with plenty of water supply in FI-CC plots and to a lesser extent in RDI-CC plots, which could encourage prominent aspects for soil quality and health restoration. Thus, the cover crop is congruent with RDI to facilitate soil functionality and water savings in a changing climate, contributing to resilient farming systems in the Mediterranean environment.

Keywords: cover crops; deficit irrigation; water stress; soil organic matter; soil microbiology; kernel yield; climate-resilient agriculture



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1. Introduction

Adaptation strategies to mitigate climate change in Mediterranean agriculture are crucial to ensure food security and reduce the vulnerability of agricultural systems [1], and this process should include integrated water and soil resources management, the promotion of sustainable agricultural practices, and crop diversification [2–5]. Resilient agriculture is an approach that involves sustainably using natural resources through crop

and livestock production systems to attain long-term productivity and farm profits under climate variability [6,7].

To address these challenges, the European Union (EU) focuses on the main objective of the Common Agricultural Policy 2021–2027: promoting practices that ensure adaptation and mitigation of climate change through investments, incentives, and improvements of final returns [8]. The use of different techniques related to sustainable and regenerative agriculture and irrigation water productivity is within this set of required actions. In this sense, the implementation of regulated deficit irrigation (RDI) strategies or the implementation of cover crops (CC) is expected to promote the sustainability, profitability, and viability of Mediterranean agroecosystems [9,10]. These actions are even more necessary in regions where agricultural intensification has provoked soil degradation, as in many rural areas of Southern Europe, where natural resources are becoming even more scarce [11,12].

Recently, European initiatives such as the Green Deal or EU Mission: A soil deal for Europe have discussed agriculture as a potential sector to favor atmosphere C sequestration, improving soil organic carbon (SOC) levels and soil health. As a result of the latest Common Agricultural Policy (CAP) 2023–2027, there has been a growing interest in practices focused on more sustainable agriculture [13–15]. In this line, the optimal management of vegetative covers in woody crops is required to incorporate production systems into one of the eco-regimes (ER) considered in the latest CAP. Although accepting these ERs is voluntary, the budgetary amount considered in the direct aid independent of production (decoupled aid) is the second in terms of amount. It requires incorporating one of the nine ERs considered in the CAP Specific Plan (PEPAC) [16], especially practices six and seven, which are specifically devoted to woody crops.

Particularly, in the Mediterranean region, several works have been conducted to demonstrate the effect of CC, achieving environmental and agronomic benefits [10,17,18]. That is, the implementation of CC based on legume (vetch, broad beans, lentils, etc.) plants or a mixture with grasses (barley) has been demonstrated to be an adequate strategy for improving soil quality terms and reducing soil degradation [19,20]. However, the combination of CC with water-saving practices such as RDI can pose a significant challenge, as these could compete with soil water resources, inducing a higher level of stress than that already endured by the crop due to drought conditions, although the final result will be determined by the species and its adaptation capability. In this context, understanding the effects of water scarcity on the soil's capability to increase the SOC is a key factor in supporting the policy and decision making on strategies to enhance the resilience of agriculture to climate change [21,22]. Moreover, water scarcity is a long-standing issue in Mediterranean countries, as recent years have seen more frequent and prolonged adverse conditions due to the changing climate [3]. Thus, it is essential to increase awareness of water use efficiency, adapt agroecosystem management to present and future conditions, and prevent scenarios where the resilience capacity is severely limited [23,24].

Almond (*Prunus dulcis* Mill.) is the second perennial crop in Spain in terms of surface (~760,000 hectares), although its cultivation has traditionally been associated with marginal and rainfed areas [25]. This crop is considered a drought-tolerant plant, and its capability of adaptation to water-scarcity scenarios offers the possibility of obtaining competitive and sustainable yields when moderate deficit-irrigation strategies are implemented [26,27].

Concretely, previous works have shown that almonds can respond positively to moderate RDI strategies, often without any reduction in yield [28,29]. This optimum capacity of adaptation to situations of moderate water stress is a great advantage, especially when the average water allocation available for this crop is low. In general terms, this supply has not exceeded $3500 \text{ m}^3 \text{ ha}^{-1}$ in the best cases, while the average water needs for almonds in S Spain are around $7000 \text{ m}^3 \text{ ha}^{-1}$ [30]. According to Mirás-Avalos et al. [31], a threshold of $3500 \text{ m}^3 \text{ ha}^{-1}$ was established at which almond production values would be seriously affected. In contrast, above this threshold, losses would be drastically reduced and could even reach values very similar to those obtained by the crop under non-water-limiting conditions. However, these results depended greatly on the variety, the management

system, the plantation age, the deficit-irrigation strategy, and the duration of stress over several consecutive seasons [32,33].

Given these considerations, its development under “more sustainable agricultural practices”, such as CC incorporation in the fields, must be considered and deeply studied in order to determine if this type of practice could worsen the crop’s yield response when grown under a moderate RDI strategy. It is well-known that one of the most critical periods for the application of water stress in the almond corresponds to its vegetative development and fruit growth [34–36], coinciding with the time of maximum growth and development of CC. Therefore, it could lead to competition for the water stored in the soil, increasing the crop stress situation and negatively affecting productivity. Thus, determining the optimal procedure for integrating the plant covers, particularly for woody crops, remains a significant challenge under water-scarcity conditions when RDI is implemented [37]. In addition, the conjunction of both strategies (RDI $\times$ CC) could enhance climate change mitigation by fixing atmospheric carbon. This approach would also help to restore soil quality and fertility while promoting agroecological biodiversity, as suggested by Ramos et al. [38] and Repullo-Ruibérriz et al. [18].

We hypothesize that an equilibrium between CC and RDI practices can be achieved, allowing us to face the double challenge of adapting to climate change (due to the scarcity of water resources) and mitigation (favoring the sequestering of atmospheric C through the biomass of plant covers) without affecting the almond yield or its nutritional status while improving soil quality and health. Thus, the objective of this study was to evaluate the effects of the application of RDI combined with CC on soil carbon storage, microbial and enzymatic activity, crop water status, and the yield of three almond cultivars (Guara, Marta, and Lauranne) throughout a three-year monitoring season in the Mediterranean environment (SW Spain).

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted during three seasons (2021–2023) in an experimental mature almond orchard at the Andalusian Institute of Agricultural and Fisheries Research and Training (IFAPA), located in Alcalá del Río, Seville (SW Spain). Trees were planted in 2016, with three representative almond cultivars (Marta, Guara, and Lauranne) for the study area in the Guadalquivir River basin, and all grafted onto GN15 rootstock. The trees are 6 $\times$ 7 m spaced, with drip irrigation using two pipelines with emitters of 2.3 L h^{−1}. The soil is a typical clayey-loam texture *Fluvisol* [39], with a depth of more than 2.5 m, fertile, and a field capacity and permanent wilt point of 0.42 and 0.17 m³ m^{−3}, respectively.

Climatic classification of the area is attenuated meso-Mediterranean, with an annual potential evapotranspiration (ET₀) rate of 1400 mm and an accumulated rainfall of 540 mm (average data corresponding to the last 15 years; obtained from the Andalusian Weather Information Network).

2.2. Field Experimental Design

The experimental orchard was formed by four treatments based on a combination of two water-irrigation strategies and two soil-management systems, following a randomized complete block with four replications (Table 1). Accordingly, (i) fully irrigated (FI) trees were irrigated, covering 100% of the irrigation requirements (II.RR), and (ii) the regulated deficit irrigation (RDI) strategy involved irrigation while applying 80% of II.RR during the vegetative stage (from March to June) and post-harvest (from harvesting to the end of October, coinciding with the beginning of autumn rainfall). Additionally, during the kernel-filling stage (from June to mid-August or the beginning of September, just before harvesting), trees were irrigated, applying 40% of II.RR. Each irrigation strategy was subjected to two soil-management systems, which were performed as follows: (i) bare soil (BS), trying to keep the soil without spontaneous plants from February until foliage fall-over, applying two chemical mowing at the beginning of February and June, and (ii) the

implementation of cover crop (CC) with a mixture of legumes and cereal (75% *Vicia sativa* L. + 25% *Avena sativa* L.), which was planted in autumn after the first rains and mechanically controlled at the beginning of April of the following year (Figure 1). On that date, the cover crop was mowed, and mulch was spread over the soil surface. Punctual herbicide applications were performed to avoid additional competition from spontaneous plants during the maximum water-demand period.

Table 1. The experimental treatments based on the irrigation water strategies and soil-management systems used.

Natural Resource	Strategy and Management Systems	
Water	Full irrigation (100% I.L.RR) (FI)	
	Regulated deficit irrigation (RDI)	
Soil	Bare soil without cover crops (BS)	
	Cover crop (legume + cereal) (CC)	
Water and soil treatments	FI-BS	RDI-BS
	FI-CC	RDI-CC



Figure 1. Experimental plots with different soil-management systems: bare soils (A) and cover crop implementation (B).

Irrigation doses were calculated according to the methodology proposed by Allen et al. [40], obtaining the values of ET_0 by using a weather station close to the experimental orchards (<500 m). The local crop coefficients used during the experimental period ranged from 0.4 to 1.2, according to García-Tejero et al. [41]. Overall, RDI receives ~50% of the irrigation water supply in FI.

Finally, routine almond cultivation techniques were used according to the regulations for integrated production for the study area (Andalusia, SW Spain). In this sense, the experimental orchard annually received NPK complex fertilizer (15-15-15, 250 kg ha⁻¹) at pre-flowering, with additional nutrients incorporated until reaching NPK units around 80-45-100; finally, pest and disease products were applied when required.

2.3. Sampling, Chemical Determinations, and Microbiological and Enzymatic Activity Measurements

Table 2 summarizes the different samplings, the timing, and the analysis developed throughout the experimental period. Soil samples were taken for each study season: (i) approximately one month after plant cover mowing (mid-May, approximately); and (ii) and at the end of the season (early October), coinciding with the beginning of leaf pulling and before the autumn sowing of plant cover for the following season. In each sampling, four replications were taken for each treatment ($n = 4$) and at three different soil depths (0–10, 10–25, and 25–50 cm); the samples taken for each treatment were randomly distributed throughout the experimental plot.

Table 2. Sampling, timing, and measurements performed.

Samples	Timing		Measurements
Soil	Spring (Mid-April)	Autumn (October)	SOC, MBC, FDA, DH, PROT, AP, GLUC
Almond leaves	Summer (Mid-June)		Mineral status (N, K, P, Na, Ca, Mg, Cu, Zn, Fe, Mn)
Almond tree	Fortnightly (from April to September)		Ψ_{stem} , yield and its components (mid-August)
Cover crop	Before sowing (April)		Dry matter

SOC, soil organic carbon; MBC, microbial biomass carbon; FDA, fluoresceine diacetate activity; DH, dehydrogenase; PROT, protease; AP, alkaline phosphatase; GLUC, β -glucosidase; Ψ_{stem} , stem water potential.

Additionally, before the plant cover was mowed, four replications ($n = 4$) were taken at random points of the plot using a 0.5×0.5 m harrow to determine the accumulated dry matter of the cover crops and its potential for C fixation via above-ground biomass. In addition, coinciding with the beginning of the kernel-filling period, four leaf samples were taken in each almond cultivar and treatment. These samples were taken around the trees, ensuring they corresponded to mature and healthy leaves.

The macro- and micronutrients in leaves were determined in accordance with the standard methods for the examination of this type of sample [42]. The SOC was analyzed following the methodology proposed by Walkley and Black [43]. Additionally, microbial activity [the hydrolysis of fluorescein diacetate activity (FDA)] was determined, as indicated by Adam and Duncan [44]. Microbial biomass carbon was analyzed using the fumigation–extraction method [45,46]. Dehydrogenase activity was determined according to Thalmann [47], and the protease was described by Ladd and Butler [48]. Finally, alkaline phosphatase activity was analyzed following the Tabatabai and Bremmer [49] protocols, and β -glucosidase was measured according to Eivazi and Tabatabai [50].

During the irrigation period, measurements of stem water potential (Ψ_{stem}) were taken at fortnightly intervals at midday (12:00 solar time). For midday Ψ_{stem} readings, the standard procedure was bagging (aluminum foil-covered plastic bags) a leaf on the tree at least 15 min before sampling from monitored trees under different treatments; this allowed it to reach equilibrium. Then, the leaves were cut off and placed in a pressure chamber with the petiole protruding out. Concretely, Ψ_{stem} was measured using a pressure chamber (Soil Moisture Equipment Corp., Sta. Barbara, CA, USA) in four trees per cultivar and treatment using one leaf per tree ($n = 4$) in three phenological stages: vegetative (P-I), kernel-filling (P-II), and post-harvest (P-III).

At the end of each season, almond production was measured in terms of the in-shell yield. Harvesting operations were performed using a mechanical vibrator and peeling to remove the hull. Later, almonds were air-dried and weighed once they reached a humidity content below 6%. For this, almond samples per monitored tree were weighed. Once the kernel unit weight (with and without the shell) was known, kernel yield was estimated by calculating their ratio. Ultimately, the irrigation water productivity (IWP) was estimated annually and for the whole study period as the almond yield divided by the total seasonal irrigation water applied (kg m^{-3}).

2.4. Statistical Analysis

Considering that all of the data were obtained in three consecutive seasons, year-to-year, an exploratory and descriptive analysis of all measurements (the nutritional status of leaves, soil measurements, and dry matter of cover crops) for each treatment was performed, checking the normality and homoscedasticity using XLSTAT Premium 2016 (Addinsoft, New York, NY, USA). After, a one-way analysis of variance (ANOVA) was performed to study the single effect of irrigation treatment and soil management and a two-way ANOVA for multiple effects, with the treatment means separated using the Tukey multiple range test at a 5% significance level. For each cultivar, the kernel yield and its components were analyzed year-to-year (kernel unit weight, the ratio between kernel weight vs. almond weight, and the IWP), applying an ANOVA with Tukey's test, considering the irrigation treatments, the soil management, and the interactions between them as factors.

As all the data were obtained in three different seasons, in order to analyze the dataset for the three seasons ($n = 12$, 4 replicates per treatment $\times$ 3 seasons), dataset normalization for each treatment and cultivar was performed, following the Sterk and Stein [51] procedures. In this regard, this methodology minimizes the variability associated with the particular conditions in each season to group the values. It allows applying an overall analysis with the entire set of data ($n = 12$) according to the following equation:

$$X_N = \left(\frac{X_i}{X_{annual}^{av}} \right) \times X_{total}^{av} \quad (1)$$

where X_N is the normalized variable for each treatment and cultivar, X_i is the single value obtained for each replication, X_{annual}^{av} is the average value for a single treatment and cultivar in a year, and X_{total}^{av} is the average value for a single treatment and cultivar during all the monitored seasons.

3. Results and Discussion

3.1. Crop Water Requirements, Irrigation Doses, Crop Water Status, and Leaf Nutrient Status

Table 3 presents the crop water requirements and irrigation doses applied during the study period. The FI strategy received irrigation doses between 6060 and 6310 $\text{m}^3 \text{ha}^{-1}$, while the RDI amounts were between 3020 and 3620 $\text{m}^3 \text{ha}^{-1}$, which was approximately 50% of the amount of water provided in the fully irrigated trees.

According to the treatment design, the RDI-CC and RDI-BS plots received the same irrigation doses, the only difference being the presence/absence of plant covers. The largest water withholdings in RDI were applied during the kernel-filling period, as was designed for this strategy at the beginning of the experiment. In this stage, during the first year, the RDI received 38% of the irrigation requirements (II.RR.), while during the second and third years of the study, the water allocations in that period were about 35% of the total II.RR.

In addition, taking advantage of the early spring rains, the RDI strategy was not subjected to stress situations during vegetative growth, except for the third year of the study, when the rainfall recorded in that period was very low. During the post-harvest period (from mid-August to the end of October) in the first year, there was hardly any stress in the RDI, while in the second and third seasons, this irrigation strategy amounted to 58 and 74% of II.RR. Thus, analyzing the whole dataset, the RDI received during the

fruit-growth, kernel-filling, and post-harvest stages amounted to 78, 36, and 70% of the II.RR., respectively, very close to the irrigation strategy initially designed.

Table 3. The rainfall, crop water requirements and evapotranspiration, and irrigation doses during the study period in each phenological stage.

Strategy		II.RR.	Rainfall	ET _C	Phenological Stage	Season
RDI	FI					
(mm)						
73	116	85	198	224	P-I	2021
156	397	406	3	408	P-II	
79	118	85	79	140	P-III	
308	631	576	280	772	Total	
67	96	75	164	190	P-I	2022
142	355	412	2	413	P-II	
93	155	164	73	215	P-III	
302	606	651	239	818	Total	
144	184	203	107	278	P-I	2023
124	313	358	25	375	P-II	
104	128	141	37	167	P-III	
362	625	702	169	820	Total	

ET_C, Crop water evapotranspiration; II.RR., irrigation requirements; FI, fully irrigated; RDI, regulated deficit irrigation; P-I, P-II, and P-III are the three main phenological stages (vegetative, kernel-filling, and post-harvest, respectively).

Figure 2 shows the average values of Ψ_{stem} for the three studied seasons in each cultivar and treatment. The greatest differences were found during the kernel-filling period, which were observed for all almond cultivars. Additionally, the presence of plant cover increased these differences; therefore, the lowest Ψ_{stem} were detected mainly in RDI-CC plots, with mean values between -1.5 and -1.7 MPa for all almond cultivars. In contrast, CC did not seem to affect the crop water status in the FI plot and, in the case of the FI-CC, improved these values with respect to the same treatment under FI-BS (-0.68 vs. -1.31 MPa in cv. Guara, -1.21 vs. -1.33 MPa in cv. Marta, and -1.37 vs. -1.42 MPa in cv. Lauranne). This fact was perceptible, and the decrease in soil water content induced by RDI could be triggered in extreme situations, decreasing the Ψ_{stem} in almond trees below -2 MPa and stomatal conductance at $0.15 \text{ mol m}^{-2} \text{ s}^{-1}$, as was outlined by Sperling et al. [52].

Throughout the vegetative growth period, even though no major irrigation restrictions were applied in RDI compared to FI, there were significant differences in the crop water status for the three cultivars. Also, throughout the post-harvest period, no significant differences were recorded among treatments in any of the monitored cultivars, showing that, at least during this period, the irrigation restrictions were not reflected, at least in terms of Ψ_{stem} , probably because of the lower crop water uptake because of the leaves' progressive senescence.

In relation to the mineral content in leaves, no significant effects were determined for the different treatments. Concretely, the average values of macronutrients (NPK) were similar in the four treatments, comparably observed for micronutrients (Fe, Cu, Zn, and Mn) (Table 4). Minor differences were observed in the Na levels, which were significantly higher for RDI-CC in cv. Guara in comparison to the remaining treatments. With this same logic, higher levels of Ca were denoted in RDI with respect to FI, occurring in the three studied almond cultivars, whereas higher levels in RDI were found for cv. Lauranne in comparison to FI plots for the case of Mg. However, Ca, Mg, and Na are elements highly related to the crop response under drought conditions, and their increase agrees with the presence of an osmoregulatory response when stomatal conductance regulation is low, as is the case for almonds, this being considered an anhysohydric species [53].

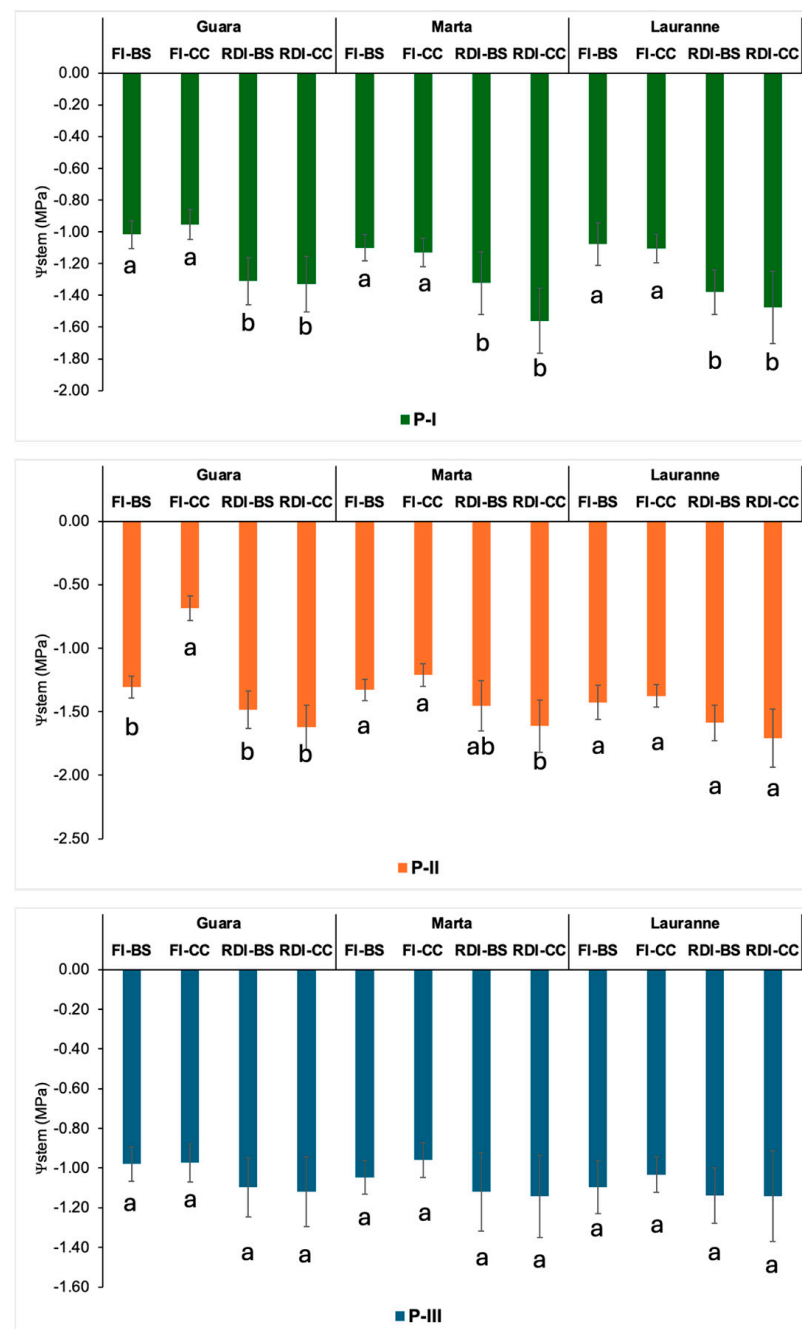


Figure 2. The stem water potential dynamics for each treatment and phenological stage in almond cultivars. FI, full irrigation; RDI, regulated deficit irrigation; BS, bare soil; CC, cover crop. Each value corresponds to the average for the three studied seasons ($n = 12$). P-I, P-II, and P-III are the three main phenological stages (vegetative, kernel-filling, and post-harvest, respectively). Vertical bars are the standard error. Different letters represent significant treatment differences ($p < 0.05$) within each phenological period.

Thus, in general, the potential competition for nutrients by plant covers that could alter the mineral nutrition of the main crop did not occur under our experimental conditions. This was presumably impossible due to the surplus of nutrient inputs associated with important amounts of the mineral fertilizers applied. However, the indisputable advantage attributable to plant cover is that they can regulate these nutrient surpluses by storing and recycling them into their tissues and, at the same time, releasing them from residues in a natural biological cycle, which is absent in bare soil.

Table 4. Leaf mineral content for each water soil treatment.

Mn (ppm)	Cu (ppm)	Zn (ppm)	Fe (ppm)	Na (ppm)	%Ca	% Mg	%K	%P	%N	Treatment	Cultivar
39.1	8.6 a	35.3 a	358.8 a	230.8 a	5.2 a	0.7 a	2.2 a	0.14 a	2.8 a	FI CC	<i>Guara</i>
37.9 a	8.2 a	34.7 a	335.9 a	210.2 a	4.8 a	0.6 a	2.7 a	0.14 a	2.9 a	FI BS	
33.7 a	9.8 a	35.0 a	397.5 a	320.4 b	7.2 b	0.8 a	2.7 a	0.13 a	2.4 a	DI CC	
32.4 a	9.9 a	33.7 a	246.9 a	232.8 a	7.0 b	0.8 a	2.6 a	0.13 a	2.1 a	DI BS	
39.7 a	11.2 a	31.6 a	326.9 a	273.4 a	4.8 a	0.5 a	2.5 a	0.14 a	2.5 a	FI CC	<i>Marta</i>
38.5 a	8.7 a	33.9 a	298.6 a	254.8 a	5.0 a	0.6 a	2.8 a	0.14 a	2.6 a	FI BS	
35.6 a	9.4 a	29.6 a	324.5 a	287.8 a	6.7 b	0.8 a	2.5 a	0.12 a	2.3 a	DI CC	
39.1 a	12.1 a	39.0 a	386.6 a	246.0 a	5.8 b	0.9 a	2.7 a	0.12 a	2.3 a	DI BS	
34.0 a	9.4 a	34.3 a	384.4 a	305.3 a	4.8 a	0.6 a	2.8 a	0.15 a	2.7 a	FI CC	<i>Lauranne</i>
35.0 a	11.2 a	33.9 a	272.3 a	260.2 a	4.9 a	0.6 a	2.7 a	0.14 a	2.8 a	FI BS	
33.1 a	8.7 a	34.1 a	340.1 a	332.8 a	8.2 b	0.9 b	2.7 a	0.13 a	2.3 a	DI CC	
36.7 a	11.3 a	37.3 a	341.4 a	290.8 a	6.8 b	0.9 b	2.8 a	0.13 a	2.4 a	DI BS	

FI, full irrigation; RDI, regulated deficit irrigation; BS, bare soil; CC, cover crop. Each value corresponds to the average for the three studied seasons ($n = 12$). Different letters represent significant differences among different treatments ($p < 0.05$) within each cultivar.

3.2. Cover Crop Dry Mass Production and Atmospheric Carbon Fixation

The treatments based on combination of plant covers with both irrigation strategies and its effect on amount of dry mass generated was marked by the rainfall amount during the months after planting, and not so much with the irrigation supply (Figure 3). That is, during the 2021 season, with a cover crop sown in autumn 2020, the average dry mass production was of 6000 and 5000 kg ha^{−1} in the FI and RDI strategies, respectively. Likewise, during the subsequent seasons, dry matter production by the cover crop was about 1400 and 1800 kg ha^{−1} in 2022, and 2400 and 2100 kg ha^{−1} in 2023 for the FI and RDI plots, respectively, with no significant differences in any of monitored seasons. It should be noted that, during 2021, the rainfall recorded from planting the cover crop to harvesting amounted to 323 mm, while during the second and third seasons, this rainfall decreased to 255 and 204 mm, respectively, which would partly explain the lower production of biomass in these seasons.

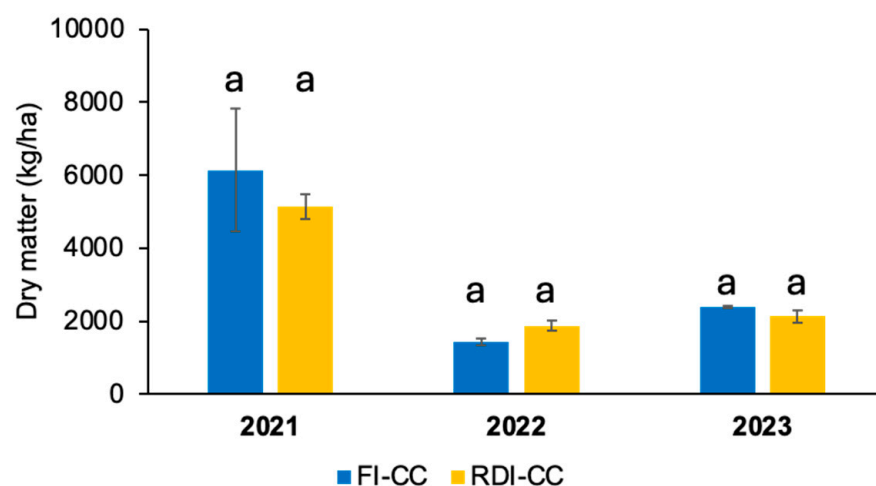


Figure 3. Average dry matter from plant covers under each irrigation strategy and monitored season for each year. FI, full irrigation; RDI, regulated deficit irrigation; CC, cover crop. Each value corresponds to the average for each treatment and season ($n = 4$). Vertical bars are the standard error. Different letters represent significant differences among treatments ($p < 0.05$).

These results of dry matter from plant covers correspond to C fixation of 38.4 and 40% for FI-CC and RDI-CC plots, respectively, which imply a C sequestration rate of

1.2 t per hectare for both treatments, evidencing the advantage of this combination for the encouragement of agricultural activity as a climate change-mitigating activity. In this sense, for a Mediterranean environment, the cover crops contributed significantly to CO₂ reduction and recycling of free-unused plant nutrients in woody fruit plantations [54].

Although the purpose of this work was not to elucidate the mechanism of plant cover-induced atmospheric C sequestration nor to appraise C balance in our production system, it was evident that above-ground plant C inputs partly explain the determined soil C gains. When considering the designed treatments, it was clear that the soil C gains and generation of biomass via C fixation were manifested in the plots with plant covers compared to those that were not grown. Therefore, implementing policies that compensate farmers for sequestering C may offset the losses in profits associated with plant cover use and provide incentives for its adoption.

3.3. Soil Organic Carbon, Microbiological Biomass, and Enzymatic Activity

Figure 4 shows the SOC and soil microbiological biomass carbon (MBC) contents for each treatment at different soil depths and during early spring and late autumn periods. The highest levels of SOC were determined, especially at the first 10 cm soil depth, following the same trend with higher contents in CC treatments than BS, with a slight increase for autumn samples with respect to the spring ones. In this line, Madejón et al. [55] stated that for a large range of soil types and environmental conditions, no-tillage operations and plant covers can effectively increase SOC rates and foster more favorable conditions, particularly in the upper soil layers. Consequently, an increase in SOC could also encourage an improvement in the water retention capacity in soils [56]. In contrast, for remaining soil depths, a declining pattern for FI-CC and FI-BS plots was found, particularly in the deeper soil layers (25–50 cm). In addition, higher SOC contents were determined in RDI-CC compared to FI-CC at 10–25 and 25–50 cm soil depths, which could be compatible with less organic matter mineralization in the most water-deficient conditions. This fact concurred with the findings of Núñez and Schipanski [57], who reported that water irrigation augments SOC contents in semi-arid agroecosystems. Finally, the amount of SOC stored in the surface soil highly depends on the cumulative effect of plant covers. In this context, Poeplau and Don [58] reported that the C inputs to the soil undergo various transformations depending on the turnover time of the plant residues, and a fraction of the added soil C remains in a stable organic form and contributes to SOC accumulation in the long term.

Soil MBC is widely recognized as the main force driving the decomposition of organic matter and is usually used as an early indicator of changes in soil parameters resulting from soil-management systems. Concretely, the MBC contents for the first two sampling depths (0–10 and 10–25 cm) were higher under full irrigation (FI-CC and FI-BS) plots than water deficit irrigation ones (RDI-CC and RDI-BS). These data align with the greater contents of SOC, as discussed before (Figure 5). Also, this agrees with the results found by Melero et al. [59], highlighting the strong correlation between SOC and MBC in soils. In addition, higher SOC rates in the autumn sampling corresponded to a lower MBC content, the exact opposite of the trend that took place in the spring sampling. Similarly, Lepcha and Devi [60] indicated that land use, soil depth, and season significantly influenced the microbial biomass carbon.

Overall, the presence or absence of plant covers did not seem to provoke important effects on SOC and MBC levels, and these values were impacted more by the irrigation supply; therefore, according to the findings, water-deficit scenarios promote a lower SOC mineralization capacity and a lower microbial biomass rate. In this sense, Wang and Klassen [61] determined that different irrigation doses did not cause significant changes in soil MBC, but the cover crops increased the soil microbiological biomass through the decomposition of organic C, especially with legume plants. Finally, according to Naylor and Coleman-Derr [62] or Schimel [63], water scarcity can determine the levels of SOC, affecting the retention and organic matter mineralization of agricultural ecosystems acting as potential carbon sinks. Recent works have demonstrated that higher soil moisture

content is directly related to higher soil respiration rates and, hence, a higher presence of biological activity is attributable to carbon released [64–66]. The findings of the present experiment are in line with those reported by these authors, registering lower MBC levels and soil enzymatic activity under deficit soil water contents in RDI plots.

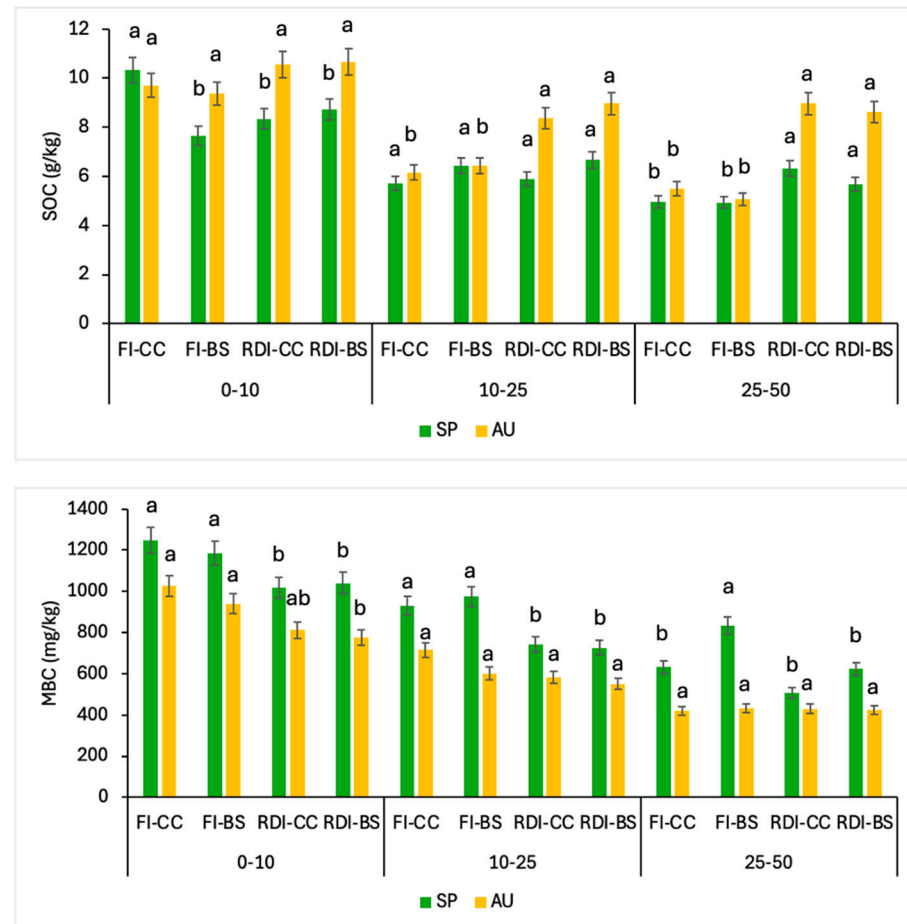


Figure 4. The soil organic carbon (SOC) and microbial biomass carbon (MBC) contents at three soil depths (0–10, 10–25, and 25–30 cm) in early spring (SP) and late autumn (AU) for each monitored treatment. Data correspond to the average of the three years ($n = 12$). FI, full irrigation; RDI, regulated deficit irrigation; BS, bare soil; CC, cover crop. Vertical bars are the standard error. Different letters show significant differences ($p < 0.05$) among treatments within each soil depth and sampling time.

Figure 5 displays the levels of the main enzymatic activities registered in the spring and autumn samplings at different soil depths for each of the studied treatments. The results showed significantly higher levels of fluorescein (FDA) activity in the treatments with cover crops (FI-CC and RDI-CC), mainly at a 10 cm soil depth, for both spring and autumn samplings, with no significant effects derived from the irrigation strategies applied. With an increasing soil depth, the FDA was significantly reduced in all treatments. Similarly, Chavarría et al. [67] highlighted that soil enzyme activities was enhanced with plant cover inclusion, particularly for FDA and dehydrogenase activity up to 35.3 and 38.1%, respectively, higher than the control treatment.

In relation to dehydrogenase activity, higher levels were fixed in the autumn period, with rate improvements in treatments with plant covers. This activity was singularly relevant until the 25 cm soil depth, with negligible values for soil samples between a 25 and 50 cm depth. Similarly, Mikanová et al. [68] found that dehydrogenase activity was higher in soil layers of 0–15 cm with no tillage, decreasing with deeper soil layers. The irrigation and, therefore, higher soil water content can raise the soil dehydrogenase activity, according to Brzezinska et al. [69,70], as was determined in our experiment. However, no important

alterations due to cover crops were reported by Nivelles et al. [71]. Among soil enzymes, dehydrogenase is considered a direct measure of soil microbial activity, indicating the level as a biological indicator of soil health [72], which was evident in the present study.

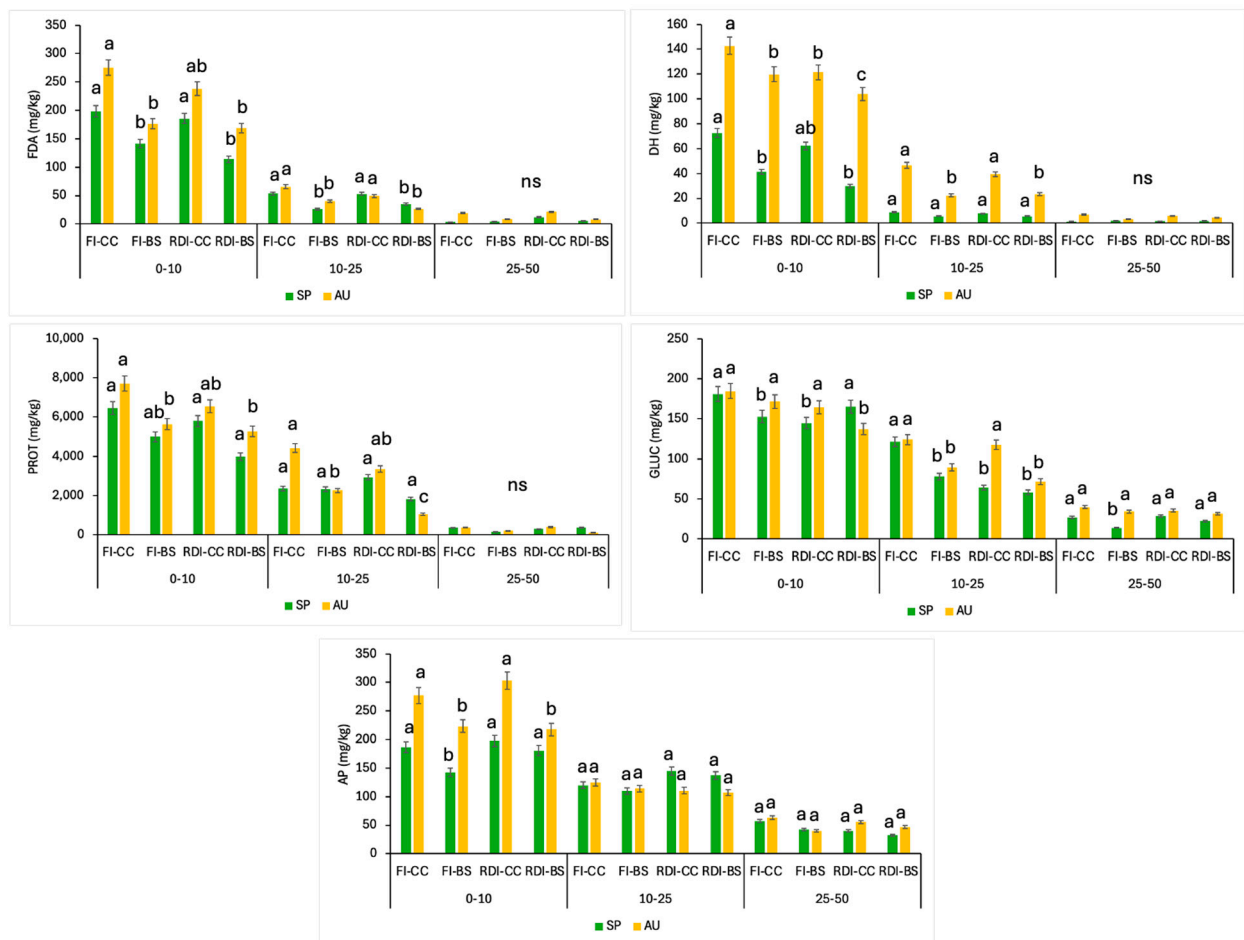


Figure 5. The levels of fluoresceine diacetate (FDA), dehydrogenase (DH), protease (PROT), glucosidase (GLUC), and alkaline phosphatase (AP) activities at different soil depths (0–10, 10–25, and 25–30 cm) in early spring (SP) and late autumn (AU) for each monitored treatment. Data correspond to the average of the three years ($n = 12$). FI, full irrigation; RDI, regulated deficit irrigation; BS, bare soil; CC, cover crop. Vertical bars are the standard error. Different letters show significant differences ($p < 0.05$) among treatments within each soil depth and sampling time.

On the other hand, the protease activity showed significantly higher values in the treatments with plant covers. In this case, the differences were smaller than those observed in the case of dehydrogenase activity. The protease activity was imperceptible at a 25–50 cm soil depth, contrasting with the levels found until a 25 cm soil depth for all treatments. The findings of the present experiment coincide with the study by Roldán et al. [73], who reported that no-till soil and legume cover significantly enhanced the soil enzyme activities (protease, dehydrogenase, β -glucosidase, and acid phosphatase, among others), which agrees singularly with the FI-CC plots at upper soil layers. The protease activity, like any other enzyme activity, depends on the soil type and decreases with the soil depth due to a reduction in organic matter content and microbial abundance [74], which is in line with the organic carbon content found in deeper soil layers in the present experiment.

The β -glucosidase activity registered the highest values for FI-CC, with declines for FI-BS and treatments with RDI strategies. A similar pattern was registered for alkaline phosphatase, with the highest values recorded at a 10 cm soil depth, with significant improvements in both FI-CC and RDI-CC plots. The β -glucosidase activity was limited

due to decreased soil moisture [75], as was denoted in plots under the RDI strategy, and depended on the soil depth [76]. In this sense, Acosta et al. [77] revealed that β -glucosidase activity decreases with soil depth, greatly depending on substrate supply and the microorganisms that produce this enzyme, which are active in the topsoil [78]. In relation to the impact of plant covers, Sinsabaugh et al. [79] stated that the no-till treatment augmented β -glucosidase activity due to enhanced microbial biomass, greater substrate availability, and reduced soil disturbance combined with cover crops, as was designed in the present study. Makoi et al. [80] outlined that leguminous plants release more phosphatase enzymes than non-leguminous plants, and both protease and phosphatase activities significantly improved after two seasons of minimum soil disturbance [81,82].

Overall, the plant covers, with their root systems, can encourage the development of porosity and infiltration, thus enabling the root zone to act as a partial sink for irrigation water (FI or RDI) applied, especially at upper soil layers. This fact increases the soil water content, which strongly influences the soil's microbial activity, community composition, and, consequently, enzymatic activities, as was pointed out by Ramos et al. [38] and Geisseler et al. [83]. This differs from non-irrigated areas, where, as soils dry, the water potential declines, and microbial activity decreases as enzyme activity slows.

3.4. Almond Yield and Its Components

Table 5 shows the almond yield in response to different treatments during the study period. According to the average data, the cv. Guara showed yield losses associated with the irrigation strategy but not with plant cover, denoting no worsening effects due to its implementation in the RDI strategy and with improvements in the case of the FI-CC plots, amounting to 1470 kg ha^{-1} .

Regarding the cv. Marta almonds, no effects were found in yield due to either the irrigation or the plant cover presence. This suggests the feasibility of combining the irrigation strategy (RDI) and soil-management system (CC) in fostering sustainable and competitive almond production. Concretely, the cv. Marta in RDI-CC plots averaged a yield of 1685 kg ha^{-1} , which is practically similar to FI-CC plots, with 1618 kg ha^{-1} , but with 50% irrigation water savings. In contrast, the cv. Lauranne showed significant effects in yield terms due to water stress and plant cover, with an even more significant reduction in RDI-CC with respect to RDI-BS plots (1332 vs. 1479 kg ha^{-1}).

By analyzing the data year by year, during the first (2021), the cv. Guara displayed significant yield losses in the RDI compared to FI plots, registering the highest production values for FI-CC. In the case of the cv. Marta, the most relevant production values were registered in RDI-CC, followed by FI-CC treatments, while the cv. Lauranne in the FI-CC had the best production values. Meanwhile, the lowest values were determined in RDI-CC plots.

In the second season in 2022, the cv. Guara again yielded the highest values in the FI-CC trees, with very significant increases in relation to the previous season. The cv. Marta also showed very considerable improvements in production values during this season, with no differences observed among the treatments. In relation to the cv. Lauranne, despite fixing significant yield increases, the RDI again showed important reductions compared to FI plots without transcendent effects due to the implementation of plant covers.

During the third year, a generalized decrease in yield was found in cvs. Guara and Lauranne with respect to the previous year, probably due to the alternate and irregular bearing of almond trees that could have generated important annual production fluctuations. The lowest production values for cv. Guara were recorded in RDI-BS (1372 kg ha^{-1}), while those for the cv. Marta were recorded in FI-CC (1709 kg ha^{-1}) plots. Regarding the cv. Lauranne, no differences were found among treatments either due to the irrigation dose or soil-management system. Thus, according to the findings, the implementation of plant covers was compatible with RDI strategies without provoking important negative effects on yield in the medium term, even with improvements in the case of scenarios without water restriction. In general, our findings agree with those highlighted by Stewart

et al. [84] in relation to the absence of important yield reductions due to the effect of RDI strategies. Many studies have reported almond yield reductions in response to deficit irrigation strategies [26,32,52,85]. Particularly, Moldero et al. [86] outlined that a shift from moderate RDI (65% ETc) to severe RDI (30% ETc) lessened yield, affecting the fruit load more than kernel weight. In this sense, Girona et al. [87] stated that a decline of 30% in irrigation water reduced the fruits per tree but not the kernel dry weight.

Table 5. Almond production and its components and irrigation water productivity for the studied seasons under each water soil treatment.

Year	cv. Guara				cv. Marta				cv. Lauranne			
	FI-BS	FI-CC	RDI-BS	RDI-CC	FI-BS	FI-CC	RDI-BS	RDI-CC	FI-BS	FI-CC	RDI-BS	RDI-CC
Yield (kg ha ⁻¹)												
2021	792 b	1071 a	487 c	500 c	764 c	1001 ab	932 b	1175 a	1180 b	1418 a	1050 b	843 c
2022	1631 a	1776 a	1433 ab	10,340 b	1993 a	2143 a	2160 a	2091 a	2249 a	2522 a	1940 b	1826 b
2023	1431 ab	1562 a	1372 b	1594 a	1921 a	1709 b	2016 a	1790 ab	1383 a	1479 a	1447 a	1328 a
2021–23	1285 ab	1470 a	1097 b	1145 b	1559 a	1618 a	1703 a	1685 a	1604 ab	1806 a	1479 b	1332 c
Kernel weight (g)												
2021	1.31 a	1.25 b	1.26 b	1.23 b	1.32 a	1.35 a	1.32 a	1.31 a	1.18 b	1.20 a	1.17 b	1.17 b
2022	1.41 a	1.42 a	1.44 a	1.42 a	1.51 a	1.47 a	1.46 a	1.38 a	1.22 a	1.28 a	1.25 a	1.19 b
2023	1.18 a	1.06 b	1.03 b	0.96 b	1.15 b	1.31 a	1.10 b	1.15 b	1.09 b	1.21 a	1.10 b	1.04 c
2021–23	1.30 a	1.24 b	1.24 b	1.20 c	1.33 b	1.37 a	1.29 c	1.28 c	1.16 b	1.23 a	1.17 b	1.13 c
Ratio												
2021	0.35 b	0.35 b	0.37 a	0.37 a	0.31 a	0.31 a	0.3 a	0.3 a	0.31 a	0.31 a	0.31 a	0.31 a
2022	0.40 a	0.40 a	0.39 a	0.39 a	0.37 a	0.37 a	0.36 a	0.36 a	0.36 a	0.36 a	0.36 a	0.36 a
2023	0.32 b	0.33 b	0.34 ab	0.35 a	0.32 b	0.32 b	0.34 a	0.32 b	0.31 a	0.31 a	0.30 a	0.32 a
2021–23	0.36 a	0.36 a	0.37 a	0.37 a	0.33 a	0.33 a	0.24 b	0.24 b	0.33 a	0.33 a	0.32 a	0.33 a
IWP (kg m ⁻³)												
2021	0.13 a	0.17 a	0.16 a	0.16 a	0.12 b	0.16 b	0.30 a	0.38 a	0.19 b	0.22 b	0.34 a	0.27 a
2022	0.27 b	0.29 b	0.48 a	0.44 a	0.33 b	0.35 b	0.72 a	0.70 a	0.37 b	0.42 b	0.64 a	0.60 a
2023	0.23 b	0.25 b	0.38 a	0.44 a	0.31 b	0.27 b	0.56 a	0.50 a	0.22 b	0.24 b	0.40 a	0.37 a
2021–23	0.21 b	0.24 b	0.34 a	0.35 a	0.25 b	0.25 b	0.53 a	0.53 a	0.26 b	0.29 b	0.46 a	0.41 a

FI, fully irrigated; BS, bare soil; RDI, regulated deficit irrigation; CC, cover crop, where the ratio corresponds with the ratio between the in-shell and fruit weight; IWP, irrigation water productivity. Different letters show significant differences ($p < 0.05$) among treatments.

In relation to almond yield components, a significant effect of treatments on grain weight was determined. That is, for cv. Guara, the lowest values were recorded in RDI-CC (1.20 g), as in the case of the cv. Lauranne (1.13 g), while for cv. Marta, the decrease in grain weight was similar to that of the RDI strategy (~1.28 g). Regarding the weight ratio, only the cv. Marta showed significant effects that were associated with irrigation, reaching the lowest value of 0.24, with no significant effects with respect to the remaining studied cultivars.

On the other hand, a significant increase in IWP was determined in the RDI for all almond cultivars ranging from 0.34 to 0.53 kg m⁻³, which highlighted the advantages of RDI strategies to face scenarios of water scarcity. In contrast, the FI strategy recorded values between 0.21 and 0.29 kg m⁻³ for three almond cultivars. Thus, there is potential for improving IWP by implementing RDI, as there are many cases of the successful use of this strategy in almond plantations, showing that it not only augments water productivity but also farmers' incomes [28,87,88]. Although there is a risk of competition for available soil water resources that could affect almond productivity, the plant covers can potentially provide improvements in rainwater infiltration and changes in root absorption zones, benefiting the tree's root exploration of deeper soil layers due to contention with them [89–91].

4. Conclusions

According to the findings of the present experiment, implementing cover crops in irrigated almond plantations based on moderate water stress does not represent an important disadvantage for the crop in nut yield terms, singularly, for the cv. Marta, which showed regular productivity. The water-stressed trees of the cv. Guara and cv. Lauranne had lower yields than fully irrigated trees, although the latter was more productive among the studied cultivars. That is, the 50% reduction in irrigation water due to regulated deficit irrigation with respect to fully irrigated trees should be adopted as the most appropriate irrigation strategy for achieving sustainable water management in almond orchards.

The water status of the crop was not significantly affected by the vegetation covers in the fully irrigated plots, except for the slightly higher effect due to the combination of deficit irrigation and the presence of the covers in plots with water-stressed trees.

The deficit-irrigation strategy seems to decrease the levels of biological activity, which slows down the mineralization of organic matter, thus decreasing carbon emissions from soil microbiological respiration. The plant covers positively impacted soil organic storage, microbial processes, and enzymatic activities ascribed to changes in the quantity and quality of the plant residues that enter the soil matrix; changes in the provision of nutrients; and physical alterations. This process was more evident in the upper soil layers without irrigation restrictions, which could tend to improve prominent aspects of soil health restoration. Overall, soil enzymes catalyze and foster decomposition and plant nutrient cycling; thus, their activities are a biological sign of enhancing soil quality. Additionally, soil enzymes reacted to soil-management systems based on cover crop implementation long before other soil quality changes were detectable. Thus, the cover crops in irrigated orchards improved soil functionality and provided the possibility of protecting the natural resources of water and soil in the context of climate change.

These findings indicate the possibility of undertaking new work aimed at studying the predominant biological communities in water-stress scenarios, as well as the development of carbon balances that allow effective quantification of the effects of deficit irrigation combined with different plant covers with various soil types, cultivars, and weather scenarios over a longer period.

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