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Effects of Cover Crops and Drip Fertigation Regime in a Young Almond Agroecosystem

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Abstract: The sustainability of woody crop agroecosystems requires continued improvements to water, nutrient and soil management. In this work, the combination of resource availability or fertigation dose with soil management practices was tested in a 2 × 2 factorial design in a drip irrigated young almond orchard. The fertigation doses were: the farmer supply at 60% of crop evapotranspiration and full nutrient requirements and the half-farmer supply at 30% of crop evapotranspiration and half nutrient requirements. The soil management practices were: bare soil and cover crops in the inter-row (mixture of grasses and legumes). Tree growth, yield, water and nutrient status, and cover crop biomass and nutrient status were determined, as well as inter-row soil C and N concentration. Results showed that the effect of resource availability was independent of soil management and vice versa. The half farmer treatment reduced tree vegetative growth and yield compared to farmer treatment, due to a negative effect on the water status, without observing a decrease in the concentration of nutrients in leaves or fruit. Trees with cover crop also reduced growth and yield compared to bare soil management. This was due to a nutritional competition, mainly of Ca, Fe, Mn and Zn, rather than to a decline in tree water status. Cover crops sequester up to 1 t/ha/year of carbon but do not increase soil organic carbon, nor soil total nitrogen. Cover crops proved to be efficient in reducing soil nitrate concentration in the topsoil and therefore has potential to prevent its leaching. Deficit fertigation and the use of cover crops can be effective practices to preserve and save water and nutrient resources in Mediterranean agroecosystems, but should be established with caution so as not to compromise the profitability of the orchard.

Keywords: yield; vegetative growth; water status; nutrient status; nutrient sequestration; cover crops

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1. Introduction

Spanish almond production is the second largest in the world. Almond (*Prunus dulcis* Mill. (D.A. Webb)) is the third most extended crop in Spain and, due to its ability to tolerate drought, it is of enormous importance for marginal areas throughout the Mediterranean Sea basin. Resource availability, specifically water and nitrogen, is the main factor limiting crop yield [1]. Improving the management of these important resources for agricultural production is of paramount relevance in current agricultural practices. In arid or semi-arid agroecosystems such as the Mediterranean, water resources and its management become even more important, and enormous efforts are being made to increase the efficiency of this resource in the main crops of the Mediterranean area [2].

The almond tree, a crop historically linked to marginal and rainfed agricultural land in SE Spain, has expanded enormously in recent years as a consequence of the beneficial effect of drip irrigation on farm profitability [3,4]. Nonetheless, as irrigation water is scarce, it is not sustainable to cover the full evapotranspiration demand (ET_c) of almond trees. Consequently, a considerable amount of research has been carried out to increase water productivity, including agronomic techniques, such as deficit and regulated deficit irrigation [5–7], or irrigation design, such as subsurface drip irrigation [8]. Besides watering, it is important to adjust nutrients' application in accordance with soil water availability and target yield. In the case of nitrogen, it is well known that it interacts strongly with soil water availability in most agricultural conditions, with a reduction in water use efficiency (WUE) caused by a N deficit and a reciprocal limitation in N-use efficiency (NUE) under water deficit [9–15]. Managing water and nutrient resources (fertigation) together can considerably improve WUE and NUE, while reducing the potential loss of nutrients from the agroecosystem, which could pollute surface and ground water bodies [16].

Cover crops (CC) have recently been shown to improve the sustainability of agroecosystems [17]. Soil management (SM) systems based on tillage and herbicide application have been a widespread practice in many fruit tree orchards; however, the negative impacts associated with these practices on soil quality, soil erosion and biodiversity threaten the sustainability of the agroecosystem [18–20]. Cover crops provide ecosystem services that favor erosion control, soil fertility, water infiltration, carbon stocks, pollination or pest control [17,21–26]. Nowadays, combining proper resource management (water and nutrients) with proper CC management is absolutely necessary for the sustainability of the agroecosystem, since ultimately CC could compete for water and nutrients with the main crop [17,27]. Studies carried out on different fruit tree species have shown that the presence of CC generally leads to a lower N extractable from the soil and a reduction in the foliar concentration of N and Cu (compared to treatments involving, e.g., tillage or herbicides) [28]. In addition, CC can decrease the trunk section of the main crop [29] and limit tree vigor [30]. The impacts varied from remarkable to insignificant [24] depending on climatic conditions (temperature and precipitation) [26], soil water availability and depth [31], degree of cover, and row management method, as well as on the removal of CC at specific phenological stages [32]. For this reason, strategies to reduce competition for water and nutrients from cover crops with the main crop have also been extensively studied, including (i) prompt removal of the vegetation [33], (ii) establishment of a strip herbicide managed along the rows with the CC developing between rows and managed by mowing periodically [17,34,35], (iii) selection of the CC species and planting designs [36], (iv) precise management of water and nutrient inputs [37], and (v) coupling CC management with the tree growth cycle [38].

Despite all this research, there is a lack of knowledge when both resource availability (both water and nutrients) and cover crops occur under critical semi-arid conditions, such as in the Mediterranean. Previous surveys combining different deficit irrigation strategies and soil management practices showed, in Mediterranean vineyards, a clear reduction in vegetative growth and yield, mainly due to the presence of CC [32,39]. Even rarer are studies that take into account the competition for nutrients between almond trees and the CC. Thus, the main objective of this work was to study, in a Mediterranean and semi-arid area, the effects of the presence/absence of CC (mix of leguminous and grasses species) under deficit resources' availability conditions on almond performance (quantitative and qualitatively) and tree physiology. Since the availability of both water and nutrients can be compromised by CC, the fertigation dose (Do) can affect their effects, as it defines the degree of dependence of trees on soil resources. A secondary objective of this work was to quantify the nutrient budget of almond agroecosystems. We hypothesized that under this condition the use of inter-row CC (separate 1.5 from the trunk) managed with herbicides in the row (1) may have no detrimental effects on water and nutrient status of young almond trees, improving WUE and NUE, and (2) can increase the soil nitrogen and organic matter content.

2. Materials and Methods

2.1. Plant Material and Field Conditions

The experiment was performed in a commercial young almond orchard (*Prunus dulcis* var. 'Belona') located in Hellín (Albacete, Spain) (38°22′53″ N, 1°30′32″ W) during three seasons (2018–2020). Trees were grafted onto GF-677 rootstock and planted in 2016 at a spacing of 7 × 5. The soil of the plot was sandy-loam textured (71.3 % sand, 17.1% silt, 11.6% clay), according to the USDA (United Sates Department of Agriculture) classification [40]. It is highly calcareous with a pH of 8.48, an electrical conductivity (EC) around 0.15 dS/m and with 1.5% of organic matter content. Concentration in soil of Olsen phosphorus was 69 mg/kg of dry soil, and extractable K, Ca, Mg and Na were 253, 6217, 334 and 15 mg/kg of dry soil, respectively. Nitrogen in the form of NO_3^- was 3 mg/kg of dry soil. Water for irrigation comes from the farmer (F) well that extracts groundwater and is located in the almond orchard. It has an EC and pH of 2.16 dS/m and 7.61, respectively, which makes it suitable for almond production [3]. The chemical composition of the irrigation water was (mg/L): K^+ 6.14, Ca^{2+} 81.0, Mg^{2+} 68.9, N-NO_3^- 11.8, Na^+ 253, Cl^- 489, SO_4^{2-} 149, HCO_3^- 188, PO_4^{3-} 0.488. The climate in this region is Mediterranean semi-arid with hot and dry summers. Meteorological data were recorded at the "La Carrichosa" weather station located 10 km apart from the experimental plot (Figure 1). The annual average values (for the 2018–2020 period) of the reference evapotranspiration (ET_o) and precipitation were 1237 and 305 mm, respectively. Trees were pruned minimally to maximize the flower number per tree.

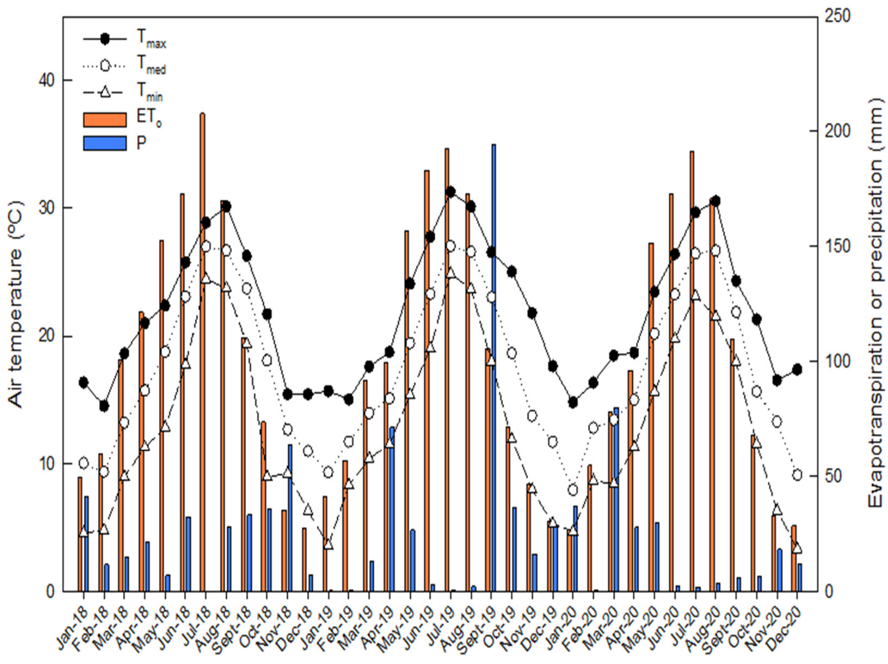

Figure 1. Monthly average maximum, minimum and mean air temperature (T_{max}, T_{min} and T_{mean}), accumulated precipitation (P) and reference evapotranspiration (ET_o) recorded from Cieza meteorological station, for the period 2018–2020.

2.2. Treatments and Experimental Design

In order to determine the effect of the fertigation dose and the presence of cover crops, a 2 × 2 factorial design was used. Therefore, four treatments were tested. Regarding the dose of fertigation (water and nutrients), there was a farmer dose (F, 60% ET_c and supply of full nutrient requirements) and half farmer dose (HF, 30% ET_c and half nutrient requirements). The soil management factor also had two levels, which were bare soil (BS) and cover crops (CC). Irrigation was scheduled using the K_c values reported by Espadafor et al. [41] and corrected with the percentage of the shaded area [42]. Water was applied through pressure compensated emitters spaced 0.75 m along two lines that were 0.5 m apart at both sides of the tree trunk. The duration and frequency of fertigation was the same for all treatments; however, the F dose was watered through 2 L/h emitters while the HF through 1 L/h emitters. The amount of water applied with irrigation was measured with online water meters. The F dose received 25–15–20, 35–20–30 and 50–30–50 kg/ha/year of N, P_2O_5 and K_2O in 2018, 2019 and 2020, respectively, while the HF received half of these amounts. Once dissolved, the fertilizers were injected into the pressurized pipe that fertigates the trees.

The CC were established inter-rows and consisted of sowing a mix of legumes and gramineous (20% *Festuca arundinacea*, 20% *Dactylis glomerata*, 20% *Lollium rigidum*, 15% *Onobrychis viciifolia*, 15% *Vicia sativa*, and 10% *Trifolium alexandrinum*). Specifically, CC were sown in January 2018 and December 2019 and re-sprouted during 2020. In the intra row, the vegetation was controlled by post-emergence herbicides, keeping a strip of 1 m free of weeds at each side of the tree. Bare soil was kept using herbicides and tillage.

The treatments were randomly replicated in a design of 3 complete blocks. Within blocks, each experimental unit consisted of 4 rows with 5 trees per row, and only the three center trees on the two center rows were used for tree determinations.

2.3. Measurements and Determinations

Vegetative growth was assessed by trunk perimeter and canopy diameter measurements on 7 November 2018, 25 September 2019 and 25 September 2020. Yield measurement was carried out on 28 August 2018, 11 September 2019 and 28 August 2020, at the time of the farmer harvest, considering 6 trees per treatment and per block. The total weight of shelled almonds per tree and number of almonds per tree were determined. The number of almonds per tree was estimated by dividing the total weight by the average fruit weight. Average fruit weight (kernel + shell) was calculated after 3 days of sun drying in samples of 250 g per experimental unit. In addition, kernel yield was determined in the same samples (kernel g per kg of kernel + shell).

Tree water status was monitored approximately every 20 days during the growing cycle (starting on 22 May 2018 and ending on 1 October 2020). The stem water potential (Ψ_s) was measured using a pressure chamber (model 3000; Soil Moisture Equipment Corp., Santa Bárbara, CA, USA), according to Scholander et al. [43]. Measurements were taken at midday (12:00 h GMT). One leaf per tree, healthy and close to the trunk, was taken from four trees per treatment and per block; leaves were previously wrapped in foil-covered bags at least 2 h before measurement. The additive effect of water deficit duration and intensity was accounted for by the water stress integral (S_Ψ) computed as the sum of plant water potential measured every day during a given period [44]. It was calculated from the Ψ_s values across the season subtracting the least negative Ψ_s value registered in a fully irrigated almond orchard by Egea et al. [45] and multiplying it by the number of days of the computed period. The S_Ψ was computed for the phenological stages II–III (rapid vegetative growth), IV (kernel-filling) and V (postharvest).

The nutritional status of almond leaves was assessed on 4 dates in 2020 (6 April, 25 June, 11 August and 25 September), while hull and kernel samples were taken on 17 August 2020. In addition, the nutritional status of CC was assessed on 28 October 2020. All samples were washed with distilled water and dried in an oven for 48 h at 65 °C. Dry tissue (leaves, hull or kernel) was ground and sent to the Ionomics Service (Research Support Service, CEBAS-CSIC, Murcia, Spain) for cations, anions and total N analysis. Cations were analyzed after digestion with HNO_3-HClO_4 (2:1) in an inductively coupled plasma spectrometry (iCAP series 6500, Thermo Fisher Scientific, Franklin, MA, USA). Anions were analyzed by ion chromatography (850 professional IC, Metrohm, Herisau, Switzerland) in water extracts obtained by shaking dried leaf material for two hours. Total N concentration was determined with an elemental analyzer (LECO TruSpec Micro Series, St. Joseph, MI, USA). Carbon, macro and micronutrient sequestration by the fruits harvested in 2020 and the CC at the end of the season (autumn 2020) was calculated from nutrient concentrations in the tissues and their dry biomass production. To obtain nutrient content in the shells, we used our dry biomass data and the N and C concentrations reported by Demirbas et al. [46] and the macro and micronutrient concentrations reported by Queirós et al. [47].

Soil sampling was carried out at the end of the experiment (28 October 2020) in the area between the tree rows (inter-rows), at a distance from the tree trunks of 3.5 m. Two disturbed composite soil samples per plot and treatment were collected at two depths, 0–20 and 20–40 cm. The disturbed soil samples were air-dried, sieved to <2 mm and analyzed in the laboratory. Total C and N were determined for bulk soils with an elemental analyzer (LECO TruSpec Micro Series, St. Joseph, MI, USA). Inorganic C (IC) was determined in the same way after soil organic matter removal by heating samples at 550 °C for 4 h. The soil organic carbon (SOC) concentration was obtained as the difference between total C and IC. $N\text{-}NO_3^-$ was analyzed by ion chromatography (850 professional IC, Metrohm, Herisau, Switzerland) after extraction with water (1:5, soil: water) and 30 min of agitation.

2.4. Analysis of Results

Multi-factor analysis of variance (ANOVA) and mean separation test for the fertigation dose (Do), soil management (SM), year (Y) and their interactions were performed. Data were analyzed using Statgraphics Centurion XVI package (version 16.0.07) (Statgraphics Technologies, The Plains, VA, USA) and graphs were obtained using SigmaPlot (version 11.0) (Systat Software, San Jose, CA, USA).

3. Results

Monthly accumulated reference evapotranspiration (ET_o) and precipitation and average air temperatures are presented in Figure 1. The recorded maximum temperatures were close to 30 °C in July–August, and minimum temperatures were close to 5 °C in January–February. Although significant rainfall events were reported on 12 and 13 September 2019 (94.1 and 87.8 mm per day, respectively), as well as a minor one on 24 March 2020 (39.8 mm), there was an important water deficit during spring and summer. On 4 April 2019, a frost hit the almond trees, which had flowered a month earlier, irreparably compromising yield. These environmental conditions occurred when trees were in a very sensitive phenological stage and consequently resulted in a significant Y × Do and Y × SM interactive effect on the number of fruits per tree and thus on yield (Table 1).

The total amount of water applied in the F treatments was 126, 135 and 326 mm in 2018, 2019 and 2020, respectively, and in the HF treatments was 61, 68 and 160 mm in 2018, 2019 and 2020, respectively. Fertigation doses (Do) as well as soil management (SM) had a clear effect on vegetative growth (trunk perimeter and canopy cover) (Table 1). Year (Y) also exerted a significant effect in these variables, without interacting with the Do and SM factors. Both vegetative growth indicators decreased as Do decreased (HF vs. F), and the soil was covered by vegetation (CC vs. BS). Similarly, yield and number of fruits per tree were affected by Do and SM, decreasing as Do decreased, and soil was covered with vegetation. Mean fruit weight was not affected by the treatments. Kernel yield, the index of dry kernel in relation to dry kernel plus shell, was slightly reduced by reducing the fertigation dose and slightly increased in trees with CC. Water use efficiency almost doubled in HF trees compared to F and also decreased in trees with CC compared to BS trees.

The effects of the treatments on tree water status were integrated over the different phenological stages across the season (Table 2). In the stages II–III, the S_Ψ showed no effect due to the treatments or year. However, the fertigation dose did affect the S_Ψ in stages IV and V, as well as in total S_Ψ across the season. Soil management also significantly affected the S_Ψ during stage V. Nevertheless, at this phenological stage, both the interaction between Y × Do and between Y × SM showed significant effects. This was due to the lack of effects in 2019 compared to 2018 and 2020. The S_Ψ was increased in HF trees compared to F ones, while the presence of the CC tended to reduce S_Ψ compared to BS management, although only significantly in 2020 during stage V.

Table 1. Effects of the fertigation dose (Do) (farmer (F) and half farmer (HF)), soil management (SM)(bare soil (BS) and cover crops (CC)), year (Y) and its interactions on vegetative growth and yield components. Water use efficiency (WUE) is shown for the year 2020. Data shows the mean ± standard error.

Year	Treatments	Trunk Perimeter (cm)	Canopy Diameter (m)	Yield (t/ha)	N° (Fruits/Tree)	Mean Fruit Weight (g)	Yield (g Kernel/100 g Kernel + Shell)	WUE (kg/m^3)
2018	F/BS	18.3 ± 0.57	2.6 ± 0.16	0.03 ± 0.010	16.0 ± 5.40	5.3 ± 0.85	31.9 ± 1.00	
	F/CC	17.1 ± 0.46	2.3 ± 0.15	0.04 ± 0.011	18.0 ± 5.97	5.5 ± 0.82	32.7 ± 0.19	
	HF/BS	15.7 ± 0.68	2.2 ± 0.29	0.04 ± 0.010	18.2 ± 4.91	5.3 ± 0.19	29.9 ± 1.03	
	HF/CC	15.1 ± 0.40	2.1 ± 0.04	0.03 ± 0.009	11.8 ± 5.00	4.8 ± 0.19	31.9 ± 0.31	
2019	F/BS	27.3 ± 0.65	3.3 ± 0.18	0.03 ± 0.024	26.3 ± 19.4	4.9 ± 0.37	27.0 ± 0.41	
	F/CC	25.3 ± 0.47	3.0 ± 0.19	0.01 ± 0.006	9.1 ± 4.66	6.2 ± 1.50	27.8 ± 0.17	
	HF/BS	23.9 ± 0.58	3.0 ± 0.14	0.01 ± 0.003	4.9 ± 2.30	6.0 ± 1.09	26.4 ± 0.03	
	HF/CC	22.6 ± 0.54	2.6 ± 0.08	0.02 ± 0.010	15.6 ± 7.66	5.3 ± 0.85	27.8 ± 0.83	
2020	F/BS	32.0 ± 0.64	3.7 ± 0.09	2.83 ± 0.140	2606 ± 112	3.8 ± 0.05	32.6 ± 0.39	0.87 ± 0.04
	F/CC	29.5 ± 0.53	3.4 ± 0.14	2.25 ± 0.155	2241 ± 157	3.5 ± 0.16	33.0 ± 0.46	0.69 ± 0.05
	HF/BS	28.0 ± 0.58	3.5 ± 0.16	2.27 ± 0.128	2141 ± 158	3.7 ± 0.10	32.1 ± 0.37	1.42 ± 0.08
	HF/CC	26.0 ± 0.53	3.1 ± 0.09	1.85 ± 0.079	1788 ± 85.2	3.6 ± 0.10	31.7 ± 0.61	1.16 ± 0.05
Year		***	***	***	***	***	**	
Do		***	***	**	*	n.s.	*	**
SM		***	***	**	*	n.s.	*	**
Y × Do		n.s.	n.s.	***	***	n.s.	n.s.	
Y × SM		n.s.	n.s.	***	**	n.s.	n.s.	
Do × SM		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Y × Do × SM		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	

n.s., *, ** and ***, means that the factor analyzed is not significant, or significant at 0.05, 0.01 and 0.001 level of probability, respectively.

Table 2. Effects of the fertigation dose (Do) (farmer (F) and half farmer (HF)), soil management (SM) (bare soil (BS) and cover crops (CC)), year (Y) and its interactions on the water stress integral (S_{Ψ}) at different phenological stages and growing season. Data shows the mean ± standard error.

Year	Treatment	S_{Ψ} (MPa Day)			
		Stage II–III	Stage IV	Stage V	Total
2018	F/BS	67.9 ± 3.9	107.4 ± 2.5	64.5 ± 1.7	239.8 ± 5.7
	F/CC	69.0 ± 2.2	109.5 ± 3.1	64.7 ± 0.8	243.3 ± 1.1
	HF/BS	77.7 ± 3.7	128.7 ± 2.1	97.5 ± 3.4	303.9 ± 5.7
	HF/CC	72.0 ± 2.3	126.6 ± 4.6	99.0 ± 1.2	296.2 ± 9.5
2019	F/BS	78.8 ± 0.8	149.5 ± 0.8	36.1 ± 1.0	264.4 ± 1.9
	F/CC	78.7 ± 3.0	153.8 ± 1.5	32.0 ± 2.6	264.5 ± 3.2
	HF/BS	80.4 ± 3.4	167.1 ± 1.6	33.0 ± 1.0	280.5 ± 4.6
	HF/CC	74.2 ± 4.4	165.7 ± 2.0	31.0 ± 1.9	270.8 ± 8.0
2020	F/BS	75.8 ± 2.4	124.8 ± 3.2	61.3 ± 1.9	261.8 ± 5.7
	F/CC	78.4 ± 3.2	120.1 ± 5.1	56.4 ± 2.1	254.9 ± 7.8
	HF/BS	69.3 ± 2.0	160.2 ± 3.2	101.2 ± 6.8	330.6 ± 11.9
	HF/CC	77.6 ± 4.9	150.8 ± 8.9	74.4 ± 2.4	302.7 ± 12.3
Year		n.s.	***	***	n.s.
Do		n.s.	***	***	***
SM		n.s.	n.s.	*	n.s.
Y × Do		n.s.	n.s.	***	*
Y × SM		n.s.	n.s.	*	n.s.
Do × SM		n.s.	n.s.	n.s.	n.s.
Y × Do × SM		n.s.	n.s.	n.s.	n.s.

n.s., *, and ***, means that the factor analyzed is not significant, or significant at 0.05,- and 0.001 level of probability, respectively.

Total phosphorus leaf concentration decreased from May to August but increased from then until September (Figure 2). In the CC treatments, total P leaf concentration was significantly lower on 25 June compared to BS treatments; however, in the last two sampling dates (11 August and 25 September), it was slightly higher than in BS treatments. Regarding fertigation dose, HF treatments showed a tendency to reduce leaf P concentration on 25 June and 11 August compared to F ones (25 June with a *p*-value of 0.056). Hull total P concentration showed a tendency to be reduced in treatments with CC compared to BS management (*p*-value = 0.058), which was not observed in the kernel. The leaf Ca concentration was also lower in the CC treatments on 25 June when compared with the BS treatments. Contrary to other nutrients (Supplemental Figures S1–S3), the Ca concentration in the leaves was very high compared with the ones found in the hull and kernel.

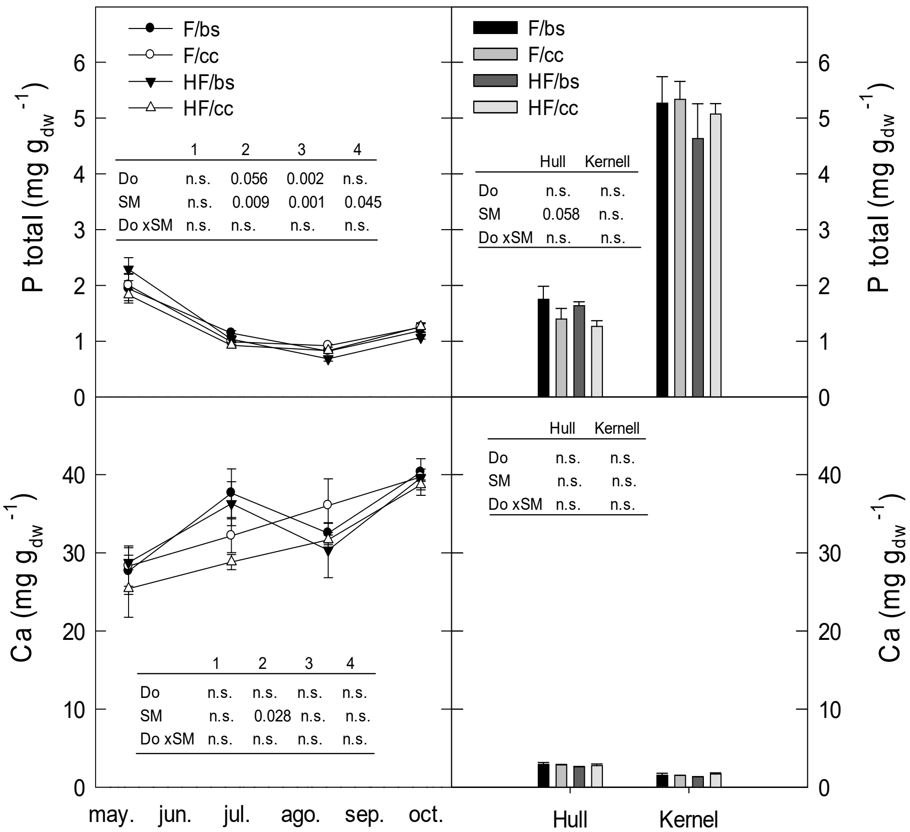

Figure 2. Effects of the fertigation dose (Do) (farmer (F) and half farmer (HF)) and soil management (SM) (bare soil (bs) and cover crops (cc)) and its interaction on the total P and Ca concentration in leaves, hull and kernel tissue in the 2020 season. Data shows the mean ± standard error. Numbers 1 to 4 indicated the leaf harvest sample date; 6 April, 25 June, 11 August and 25 September, respectively. N.s. means that the factor analyzed is not significant, and when significant the *p*-value is included.

Leaf total N concentration tended to decrease until it reached a plateau between August and September, with no significant differences between treatments and without interaction between Do and SM (Supplemental Figure S1). Neither kernel nor hull N concentration was affected by the treatments, the hull tissue being the one with the lowest N concentration. Contrary to total N, leaf N-NO_3^- concentration increased from June to August without significant differences among the treatments. The lowest value in the hull of N-NO_3^- concentration was recorded in F/CC treatment, but with no significant differences among the treatments. There were not differences in the leaf P-PO_4^{3-} concentration in the different sampling dates; however, in the hull tissue, the CC treatments significantly reduced the P-PO_4^{3-} concentrations compared to the BS ones, with no effect on the kernel.

Regarding potassium content evolution in the different tissues in 2020, it showed a tendency to decrease during the vegetative cycle, with no significant differences among the treatments or interaction between factors (Supplemental Figure S2). The highest K tissue concentration values were found in the hull and the lowest in the kernel. There was not an effect of the treatments on the Mg tissue concentration, being like the Ca, much lower in the hull and kernel than in the leaves. There was no effect of the treatments on the total S tissue concentration, finding the lowest tissue concentration in the hull.

The leaf Fe concentration trend showed an increase through the vegetative cycle (Figure 3). The SM treatments significantly reduced leaf Fe on 25 June compared to BS treatments. The lowest Fe tissue concentration was found in the kernel. The leaf Mn and Zn concentrations showed a decreasing trend until the minimum was reached on 11 August, then increased. Like Fe, the leaf Mn concentration decreased significantly in the CC treatments on 25 June compared to the BS treatments. The concentration of Mn in hull and kernel was lower than in the leaves. Regarding the SM, the BS tended to reduce the Zn leaf concentration compared with the CC (25 June *p*-value = 0.069 and 25 September *p*-value = 0.049), without significant differences in hull or kernel Zn concentration. Hull Zn tissue concentration was lower than in the kernel. The leaf and kernel tissue B concentration was neither affected by the Do nor by SM treatments; however, in the hull, HF fertigation reduced B concentration compared to the F fertigation practice (Supplemental Figure S3).

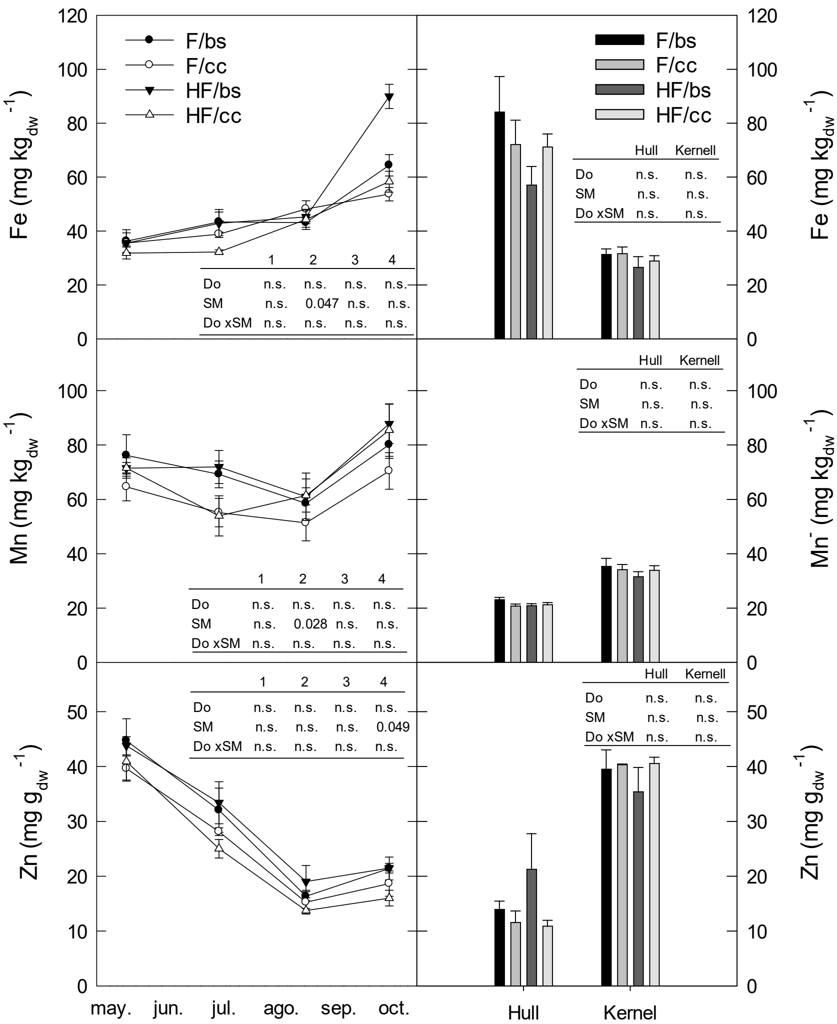

Figure 3. Effects of the fertigation dose (Do)(farmer (F) and half farmer (HF)), soil management (SM) (bare soil (bs) and cover crops (cc)) and its interaction on the Fe, Mn and Zn concentration in leaves, hull and kernel tissue in the 2020 season. Data shows the mean ± standard error. Numbers 1 to 4 indicated the leaf harvest sample date; 6 April, 25 June, 11 August and 25 September, respectively. means that the factor analyzed is not significant, and when significant the *p*-value is included.

There were no differences in CC biomass between fertigation treatments (Table 3). There were also no differences in the concentration of macronutrients, nor in Fe and B micronutrients. However, the concentration of Mn and Zn in the CC was higher in the trees fertigated with the F dose than with the HF one.

Table 3. Effects of the fertigation dose (farmer (F) and half farmer (HF)) on the biomass production of the cover crops (CC) and concentration of mineral nutrients at the end of the experiment (20 October 2020). The leaf mineral concentration in the almond, averaging the May and June sampling, is also shown. Data shows mean ± standard error.

Treat.	Biomass (g_{dw}/m^2)	N total	P Total	K	Ca	Mg	S	Fe	Mn	Zn	B
		mg/g_{dw}						mg/kg_{dw}			
F/CC	283.8 ± 29.2	8.01 ± 0.19	0.99 ± 0.04	3.08 ± 0.16	6.55 ± 0.50	1.67 ± 0.04	0.66 ± 0.01	112.8 ± 13.8	52.4 ± 10.5	34.2 ± 7.02	16.9 ± 2.16
HF/CC	308.4 ± 6.56	7.58 ± 0.41	1.14 ± 0.16	3.10 ± 0.24	6.37 ± 0.35	1.59 ± 0.09	0.70 ± 0.04	101.0 ± 18.9	35.8 ± 4.66	24.6 ± 1.58	11.9 ± 4.60
	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	***	***	n.s.
Almond leaves (May–June)		29.3 ± 0.93	1.52 ± 0.11	22.9 ± 0.62	30.6 ± 1.14	7.61 ± 0.48	1.57 ± 0.03	37.1 ± 1.26	66.7 ± 2.29	36.0 ± 1.68	21.0 ± 0.3

N.s., and ***, means that the factor analyzed is not significant, or significant at 0.001 level of probability, respectively.

The almond trees accumulated in the fruit approximately 2000 kg of C per ha and per season, being preferentially partitioned in the shell (Table 4). The sum of the nutrient content in the different tissues of the almond fruit showed the highest demand in N and K, with values close to 71 kg/ha. These nutrients were followed by P and Ca, with values close to 8 kg/ha, then Mg with 5 kg/ha and finally S with 2.17 kg/ha. Among the micronutrients, the highest demand of the fruit was in Fe with 3.6 kg/ha, followed by Mn and B, with approximately 0.12 kg/ha, followed by zinc and copper. From the distribution of macronutrients among the different tissues of the fruit, K accumulates preferentially in the hull and P and N in the kernel. As for micronutrients, Fe and Mn accumulate preferentially in the shell and Zn in the kernel (Table 4).

Table 4. Carbon and mineral nutrient uptake in the trees with farmer fertigation and bare soil management and sequestration of nutrients in the shoot of the cover crops (CC). Data shows the mean ± standard error.

C and Macronutrients		Hull	Shell	kernel	Total Almond	CC
C total		498.4 ± 43.0	1146.2 ± 72.7	400.2 ± 23.8	2044.9	979.2 ± 50.8
N total		8.63 ± 0.46	23.6 ± 1.49	39.0 ± 2.47	71.2	16.5 ± 1.04
P total		1.99 ± 0.41	0.82 ± 0.05	5.06 ± 0.28	7.87	2.27 ± 0.24
K	Kg/ha	48.9 ± 2.08	14.4 ± 0.91	8.00 ± 0.37	71.2	6.53 ± 0.46
Ca		3.49 ± 0.08	3.36 ± 0.21	1.56 ± 0.10	8.42	13.4 ± 0.64
Mg		1.61 ± 0.08	1.07 ± 0.07	2.31 ± 0.08	5.00	3.43 ± 0.20
S		0.42 ± 0.02	0.62 ± 0.04	1.14 ± 0.03	2.17	1.44 ± 0.08
Micronutrients						
Fe		93.2 ± 4.47	3516.9 ± 223	29.7 ± 1.61	3639.8	222.5 ± 26.7
Mn		24.0 ± 0.35	63.2 ± 4.01	30.8 ± 1.10	118.0	88.9 ± 10.0
Zn	g/ha	14.8 ± 1.98	21.0 ± 1.33	37.5 ± 0.72	73.2	59.6 ± 6.08
B		62.1 ± 3.21	23.6 ± 1.49	51.3 ± 8.01	137.0	29.6 ± 5.26
Cu		7.14 ± 0.62	6.86 ± 0.43	5.82 ± 0.74	19.8	18.9 ± 2.58

The CC sequestered approximately 1000 kg/ha of C per season (Table 4). The greatest demand of CC for nutrients was for N and Ca, followed by K, Mg, P and S. Regarding micronutrients, the CC has the highest demand for Fe, followed by Mg and Zn, and to a lesser extent B and Cu. The demand for macro and micronutrients of CC was overall lower than the demand for the almond trees. Nevertheless, the total demand of Ca, Mg, Mn, Zn and Cu was fairly similar between almond fruits and CC.

Total soil carbon was not affected by fertigation dose in any soil depth, but it was affected by soil management, being lower in areas with CC (Supplemental Figure S4, Table 5). Soil organic carbon and total N decreased with depth but showed no differences among treatments. In the first soil layer, the concentration of nitrogen in the form of NO_3^- was much higher in the BS than in the CC, with no effect in the deepest layer, where the N-NO_3^- concentration was similar among treatments (Figure 4).

Table 5. Effects of the fertigation dose (Do), soil management (SM) and the soil depth (De) and its interactions on the total soil carbon (Total C), total soil organic carbon (Total org C), total soil N (Total N) and soil N-NO_3^- concentration.

Effect	Total C	Total org C	Total N	N-NO_3^-
Dose (Do)	n.s.	n.s.	n.s.	n.s.
Soil Manag. (SM)	**	n.s.	n.s.	*
Depth (De)	n.s.	***	**	***
Do × SM	n.s.	n.s.	n.s.	n.s.
Do × De	n.s.	n.s.	n.s.	n.s.
SM × De	n.s.	n.s.	n.s.	n.s.
Do × SM × De	n.s.	n.s.	n.s.	n.s.

N.s., *, ** and ***, means that the factor analyzed is not significant, or significant at 0.05, 0.01 and 0.001 level of probability, respectively.

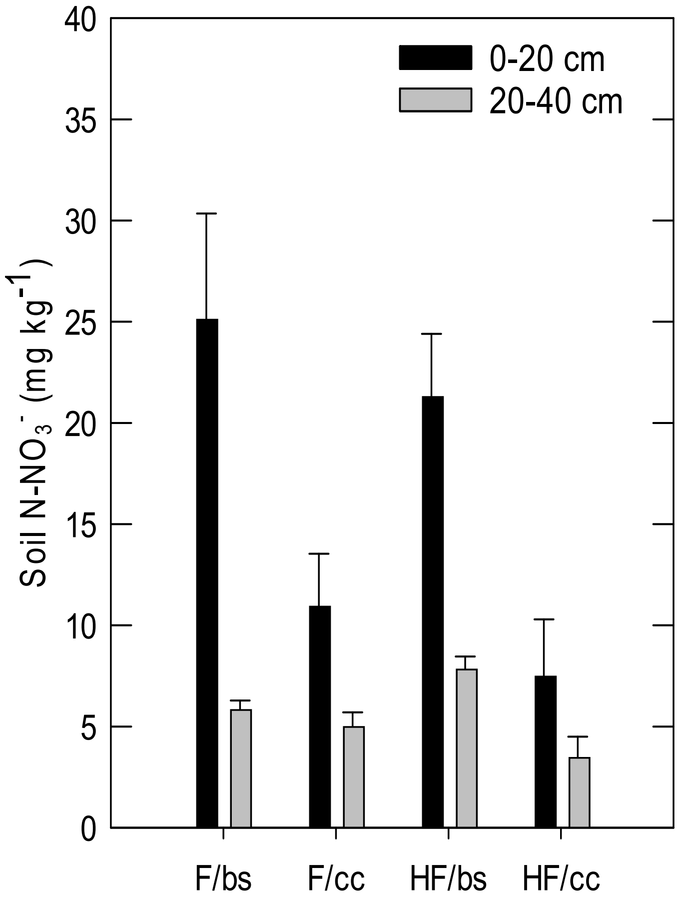

Figure 4. Effects of the fertigation dose (farmer (F) and half farmer (HF)) and soil management (bare soil (bs) and cover crops (cc)) on the soil N-NO_3^- concentration at two depths. Data shows the mean ± standard error.

4. Discussion

The coordinated management of the two major resources (water and nutrients) through fertigation to improve crop yields and reduce environmental impact is of crucial importance. Efficiency of water and nutrient use should, in fact, be jointly assessed in an attempt to simultaneously improve the use of both external resources by the crop. This is particularly important in semi-arid environments, where cover crops and spontaneous vegetation could compete for the scarce water resources and the nutrients dissolved in this water. Here we explored two experimental factors: resource availability (Do; dose of fertigation) and soil management (SM; presence/absence of cover crop), which did not clearly interact on the almond tree parameters studied (growth, yield, water and nutrient status), suggesting that in our experimental conditions the effect of the orchard inter-row managed was not dependent on the resource availably.

Very few studies analyze the interaction between Do and CC. Similar to our findings, in a low-vigor vineyard also under Mediterranean conditions, and combining deficit irrigation strategies (RDI, PRD and SDI) with the same two soil managements as in our study, no interaction was found on the growth and yield parameters studied [39]. To explain the lack of interaction in our study, it should be noted that the intra-row (1 m on each side of the tree) was treated with herbicides that could have prevented the roots of the cover crops from reaching the wet soil bulb, where water and nutrients were released by drip irrigation. Therefore, SM of the inter-row did not depend on the Do and found no clear interactions on the almond tree parameters studied. Given the lack of interaction, we discuss separately the effect of Do and SM on tree performance and finish by examining how the presence of CC has affected soil quality, specifically, carbon and nitrogen content. Moreover, a quantitative assessment of nutrient extractions is provided, considering separately almond kernel, shell and hull and cover crops' extraction (Table 4).

4.1. Fertigation Regime (Do)

The results obtained in this newly established almond orchard indicate that it is possible to obtain competitive yields with significant water and nutrient savings (Table 1). The farmer treatment (F) has an approximate reduction of 30% with respect to the total needs of the almond trees, calculated with the FAO Penman–Monteith combination method [41,42,48], so that the trees with the half dose are actually 33% of the ET_c. On the control trees (F/bs), in the third year of cultivation, the fifth year after planting, yields were close to 10 kg (kernel + shell) per almond tree, which is about 918 kg/ha of kernel (Table 1). This yield in irrigated fifth-year-old almond trees can be considered high for the standards for the region. For example, at the fifth year after planting (fourth after grafting), the mean kernel yield in almond cv. 'Marta' in Cartagena (Murcia) was 705 kg/ha [45]; in Reus (Catalonia), at the fourth year after planting, yield at 70% ET_c was close to 800 kg/ha [49]. In the half the farmer's fertigation dose (HF), tree growth was limited since the first year. In the third year, this treatment showed a reduction in trunk perimeter and canopy diameter of 12.5% and 6.43%, respectively (Table 1). The lighter decrease in canopy cover than in trunk diameter might be due to winter pruning, which, although not very severe, reduced growth proportionally more in the control trees than in the half-fertigate trees. This reduction in growth in the HF treatment was accompanied by a reduction in the number of fruits, not in fruit size, which resulted in a 19.6% drop in yield at kernel + shell basis compared to the F treatment. This resulted in an increase in water and nutrient use efficiency by 63% in the HF trees compared with the F ones. From an agronomic and farm profitability point of view, this result should be evaluated carefully, since, despite the increase in efficiency, in the third year, there is already a certain drop in yield. This suggests that this severe fertigation reduction would not be very advisable during the establishment phase of the tree, as it directly affects the size of the trees, and consequently would delay the entry of the trees to full production (4–6 years) [45]. Other studies, however, indicated that early application of deficit irrigation (DI) strategies in almond orchards did not affect their financial feasibility more negatively than when DI strategies were established once the trees are fully developed [6,45]. Some studies even point out that irrigating at 60–30% ET_c sustained throughout the season appears to be a promising DI option for arid regions [45]. These differences among studies may respond to the severe restriction applied in our HF treatment.

Overall, the detrimental response of almonds to resource availability in terms of growth and yield when reducing water dose is well documented in the literature [5,7,45,49]. A reduction of irrigation from moderate (75–60% ET_c) to severe (60–30% of ET_c) reduced pruning dry weight (in two out of six year), trunk-cross-sectional area, kernel yield and crop load [45]. In another study, in agreement with our results, a decrease of 30% in water supply decreased the number of fruits per tree but not the individual kernel dry weight [49]. Similar results were reported recently in a long-term study, where a change from moderate RDI (65% ET_c) to severe RDI (30% ET_c) reduced yield, affecting more fruit load than kernel weight [5]. According to our observations, the reduction in growth and yield was related to the water stress suffered by the trees (Table 2), as the tree nutritional status in stages of rapid vegetative growth and kernel-filling (May–June) [50,51] was not affected by the Do (Figures 2 and 3, Supplemental Figures S1–S3). This negative impact on the tree water status was indicated by the increase of the S_Ψ in the HF treatment observed during the kernel-filling (stage IV, from end of May to end of August) in every season. In 2019, differences due to the Do were not observed at stage V due to a heavy rainfall event that occurred in September.

Regarding the effects on soil chemical composition due to variations in resource supply, the reduction in fertigation did not alter the amount of nutrients at the two depths sampled (data not shown). This lack of effect in the amount of nutrients in the soil dripper zone could be explained by the greater absorption and use of nutrients in the F trees compared to the HF trees in order to sustain yields and vegetative growth. The higher uptake of nutrients in the biggest trees is evident when observing and comparing the concentration of nutrients in leaves and fruits in these trees with that of the smallest trees, since they are equal or very similar (Figures 2 and 3, Supplemental Figures S1–S3). It demonstrates that the almond tree can maintain nutritional homeostasis at the leaf and fruit level under contrasting growing conditions. These results are in agreement with the literature that points out that the almond tree has a high capacity to maintain optimal nutrient levels in spite of being exposed to different conditions/treatments; for example, almonds trees subjected to partial root-zone drying (PRD) at 30% of ET_c maintained the concentration of nitrogen in leaves similar to full irrigate trees (100% ET_c), which indicates that nutrient uptake by the tree was not limited either by PRD or severe water shortage [52]. In mature almonds trees, severe water stress reduced nonstructural carbohydrate concentration in several tissues, while N was not affected by water stress [53]. Similarly, but in almond fruits, Lipan et al. [54] did not find differences between the full irrigate treatment and the sustainable deficit irrigation treatment (26% of ET_c) in the raw almond fruits in the concentration of Ca, Mg, K, Fe, Cu, Mg and Zn. This capacity of the almond to keep stable nutrient concentration in tissues could also be related to the intrinsic nature of the *Prunus* species and wild almond species, naturally occurring in drought and non-fertile habitats [55,56]. Moreover, the specific characteristics of the GF677 rootstock, suitable for calcareous, poorly irrigated and fertile soils, may be playing an important role in the nutritional homeostasis of almonds [57]. Under our low resource supply treatment (HF), almond trees reduced canopy cover and likely increased root-to-shoot ratio [58], which could facilitate the uptake of nutrients in order to kept nutrient homeostasis.

4.2. Soil Management (SM)

Soil management is a key factor in the crop's capacity to obtain water and nutrients from the soil. In this regard, our results consistently show a decrease in the almond vegetative growth (trunk perimeter and canopy cover) of the trees with cover crops (CC) inter-rows compared with trees with bare soil (BS) (Table 1). In addition, in the third year, when there was high fruit yield, the CC decreased fruit yield by 26% on average compared to the BS treatments. This decrease in yield due to CC was caused by a decrease in the number of fruits per tree—related to canopy volume—which translated into a reduction in WUE (Table 1). A previous meta-analysis on intercropping management in Mediterranean orchards by Morugan-Coronado et al. [59] concluded that under warm and arid conditions yield could be detrimentally affected under no-tillage conditions. Our results corroborate those conclusions and point out that the CC effects on the young almond trees' growth and yield were due to nutritional rather than water competition (Table 2 and Figures 2 and 3). Our results indicate that there was no effect on tree water status across the season in response to SM, with the exception of stage V (Table 2). In 2020, the S_{Ψ} was lower under CC than under BS (Table 2). This indicates that, contrary to what was expected, at the third year, there was no water competition, but an improvement of tree water status when using CC. This could be explained by improvements in rainwater infiltration and also by changes in root absorption zones, i.e., root exploration of deeper soil layers due to competition with CC [23,33,59]. On the other hand, it may have been competition for nutrients that could have affected canopy growth, and therefore yield, at certain stages of tree development. Regarding macronutrients, there was a small but significant decrease at the end of June in P and a larger decrease in Ca in the leaves of the trees with CC compared to the BS trees (Figure 2). Regarding microelements (Fe, Mn and Zn), there was also a decrease in the CC trees, especially at the end of June (Figure 3). The decrease in macro and micronutrients in trees in response to CC matched periods with higher nutrient demand and nutrient uptake, the kernel fill and rapid root growth [50,51]. In the case of Zn, it is important to note that in all sampling dates, the leaf concentration in the trees with CC was always lower than in the BS treatment, although only the fourth sample exceeded the umbral value of 95% probability.

Overall, our nutrient status results suggest that some nutrients, specifically Ca and micronutrients Fe, Mn and Zn, may have not been fully available or not in enough quantities in periods of peak nutrient demand due to competition with CC (Figure 2). Other nutrients, such as N, P, K, S and B, are stored mostly in perennial tissues and may be less dependent on soil availability [60]. There are abundant SM studies dealing with soil fertility; however, reports assessing the tree crop nutritional status and productivity in response to SM are less frequent and mostly focused on olive, vines and apple [17]. In general, this literature points out that CC not properly managed can compete for nutrients with the fruit trees, and that legumes, in comparison with other vegetation (herbaceous vegetation), may favor N and P tree nutrition. In almonds, a decrease in foliar N and intrinsic water use efficiency and crop yield was reported in almond when changed from reduced tillage to no tillage [61], indicating that tillage practices strongly affect plant nutrition. In our trial, despite the fact that roots of the CC may not have been able to compete for the nutrients supplied to the almond trees by drip irrigation, the almond tree roots might have been competing for soil nutrients in the CC zone. The decrease in Ca, Mn, Zn and Fe concentration in the almond leaves under CC, coupled with the lower concentration of Mn and Zn in the CC biomass under the HF treatment (Table 3), suggests that almond roots competed for these nutrients with the CC. To support this, it is recognized that most of the almond tree root system under drip irrigation is spread horizontally in the upper part (30 cm) where water and nutrients are absorbed [62,63], and that most active roots develop in the topsoil where organic matter content is highest [64]. In our experiment, this can be supported by the fact that the soil organic matter content is significantly higher in the first 20 cm than between 20 and 40 cm (Supplemental Figure S4). Consistent with this is the high demand for Fe, Mn and Zn of the CC, as reflected in the concentration of nutrients in CC tissues compared to those of almond leaves (Table 4). Likewise are the total amounts of Ca, Mn and Zn sequestered by CC, which are highest (in the case of Ca) or relatively high compared with the total amounts of Ca, Mn and Zn sequestered in the almond fruits. Therefore, it can be suggested that there was some competition in the use of nutrients, especially micronutrients, in the root influence zone of the CC, resulting in low values of these micronutrients in almond leaves with CC. This could ultimately have slowed growth with respect to trees under BS

(Table 1), a mechanism that could make it possible to maintain nutritional homeostasis (Figures 2 and 3, Supplemental Figures S1–S3).

The nutrient extraction by fruits of the 'Belona' cultivar in the five-year-old trees (Table 4), and with a kernel production of 0.92 t/ha (Table 1), were within the range of 53 to 75, 5–11 and 42–143 kg/ha of N, P and K, respectively, reported by Alonso et al. [65] in an ample selection of almond cultivars, although not including 'Belona'. However, in a recent study under controlled lysimeter conditions, it has been reported that macronutrient requirements may be higher [66]. In addition to the values for macronutrients, our work also reports extraction values for micronutrients (Table 4). Moreover, we have distinguished among hull, shell and kernel. All these data are very useful to calculate a nutritional budget. For instance, if the almond is shelled on the plot and the hull tissue is left on the soil, this concentration of nutrients should be not in the balance of extractions, just as CC is not, as it would imply a temporary sequestration, until its mineralization. In general, for the 'Belona' variety on GF677 rootstock, the data shows that N and K extractions are similar and much higher than the rest of the nutrients. P and Ca extractions are also similar, around 8 kg/ha, and finally, in order of importance, Mg and S. Among the micronutrients, there is a high extraction of Fe, followed by Mn and B, Zn and finally Cu. All these data complete the existing knowledge and can be very useful for precise fertilization programs for this almond variety.

4.3. Soil C and N Concentration

At the end of the experiment, traditional BS management was compared to CC management in terms of soil organic carbon (SOC) and nitrogen concentration (Table 5, Supplemental Figure S4). Cover crops (grasses and legumes) after three years neither increased SOC nor the nitrogen content in the soil, which contradicts other studies under Mediterranean and semiarid conditions, where CC increased SOC [25,29,37,67]. Nevertheless, there are also studies under semiarid conditions where CC have minimal impact on carbon sequestered in soil [68]. The limited effectiveness of CC management in increasing SOC may be attributed to the high initial level of SOC in our experimental plot. García-Díaz et al. [69] analyzed one hundred vineyards in semiarid climates, and after five years of CC adoption, the carbon sequestration rate varied from 0 in soils with SOC content higher than 6.6 g/kg/y to 0.2 g/kg/year in soils with lower SOC levels. This may also explain why our soil did not increase SOC, since the experiment began in 2017 with an overall SOC of 8.66 g/kg (data calculated from the organic matter concentration).

A mix of grasses and legumes as CC was established, aiming to improve soil fertility and reduce nitrate loss by leaching. These mixtures represented the best compromise between biomass production, N retention, N supply via biological N fixation and water maintenance [70,71]. Moreover, as observed in our trial, CC used mineral nitrate during its growth cycle, reducing the N-NO_3^- concentration in soil (Figure 4), and therefore the potential to lose it through leaching [72]. Our soil conditions with high organic matter (1.49%) in the topsoil favors organic N mineralization and nitrate leaching [73]. With regard to total N concentration in soil, the expected decrease after three years of tillage and BS, or the expected increase under no tillage and CC with legumes [74], was not observed. This can be explained by the requirements of longer periods of time for these effects to be observed in the soil under semiarid conditions [75,76]. With regards to mineral nitrogen, the literature agrees that non-legume–legume CC mixtures are effective in reducing N-NO_3^- leaching as effectively as non-legumes, by 56% on average [77], and that greater efficacy to reduce nitrate leaching is evident with increasing soil sand content [72]. The N-NO_3^- reductions found under the CC in our almond agroecosystem sandy loam texture confirms many prior studies showing that, under appropriated conditions, CC can provide ecosystem services, such as decreasing N-NO_3^- leaching risk and protecting water quality.

5. Conclusions

During the almond tree establishment, the half farmer treatment, irrigated at 30% ET_c and fertilized at 50% of crop requirements, obtained satisfactory yields (−19%) compared to the farmer treatment, irrigated at 60% ET_c and fully fertilized. The decline in tree water status, but not nutritional status at low fertigation dose, highlights the complexity of adjusting nutrient requirements under deficit irrigation conditions, which may lead to a waste of nutrients and a source of pollution. This effect was independent of the presence of cover crops, since, regardless of the fertigation dose, cover crops inter-row reduced tree growth and yield due to competition for nutrients. Cover crops did not increase soil N or C stock but decreased mineral N-NO_3^- in the topsoil. Implementing management techniques, such as limited resource supply (water and nutrients) coupled with the use of cover crops, can improve the sustainability of the Mediterranean orchards. However, special attention should be paid to prevent resource competition leading to reduced profitability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12112606/s1, Figure S1: Effects of the fertigation dose (Do)(farmer (F) and half farmer (HF)) and soil management (SM) (bare soil (bs) and cover crops (cc)) and its interactions on the total N, N-NO_3^- and P-PO_4^{3-} concentration in leaves, hull and kernel tissue in the 2020 season. Numbers 1 to 4 indicated the leaf harvest sample date; 6 April, 25 June, 11 August and 25 September, respectively. Data shows the mean ± standard error. N.s., means that the factor analyzed is not significant, and when significant the *p*-value is included. Figure S2: Effects of the fertigation dose (Do)(farmer (F) and half farmer (HF)) and soil management (SM) (bare soil (bs) and cover crops (cc)) and its interactions on the K, Mg and total S concentration in leaves, hull and kernel tissue in the 2020 season. Numbers 1 to 4 indicated the leaf harvest sample date; 6 April, 25 June, 11 August and 25 September, respectively. Data shows the mean ± standard error. N.s., means that the factor analyzed is not significant, and when significant the *p*-value is included. Figure S3: Effects of the fertigation dose (Do)(farmer (F) and half farmer (HF)) and soil management (SM) (bare soil (bs) and cover crops (cc)) and its interactions on B concentration in leaves, hull and kernel tissue in the 2020 season. Numbers 1 to 4 indicated the leaf harvest sample date; 6 April, 25 June, 11 August and 25 September, respectively. Data shows the mean ± standard error. N.s., means that the factor analyzed is not significant, and when significant the *p*-value is included. Figure S4: Effects of the fertigation dose (farmer (F) and half farmer (HF)) and soil management (bare soil (bs) and cover crops (cc)) on the soil total C, org C and total N concentration at two depths. Data shows the mean ± standard error.

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