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White Lupin and Hairy Vetch as Green Manures: Impacts on Yield and Nutrient Cycling in an Organic Almond Orchard

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Abstract

Organic farming systems, which prohibit synthetic fertilizers, often rely on legumes for their ability to fix atmospheric nitrogen (N). In orchards, legumes can be established as cover crops between tree rows to enhance nutrient cycling. This study evaluated the effects of two legume cover crops, white lupin (*Lupinus albus* L.) and hairy vetch (*Vicia villosa* Roth), compared to a Control treatment with conventional tillage, which is the most commonly used method of soil management in the region, in an organically managed almond [*Prunus dulcis* (Mill.) D.A.Webb] orchard compliant with European Union standards, in an experiment arranged as a completely randomized design. In the first year, kernel yield was highest in the Control treatment (404 kg ha^{-1}), while significantly lower yields were recorded for white lupin (246 kg ha^{-1}) and hairy vetch (283 kg ha^{-1}), likely due to competition for resources between cover crops and trees. In the second year, however, the trend reversed, with cover crop treatments yielding significantly more (Lupin: 313 kg ha^{-1}; Vetch: 296 kg ha^{-1}) than the Control (199 kg ha^{-1}). The cover crops accumulated over 150 kg ha^{-1} of N in their tissues, enhancing soil N availability and increasing N concentrations in almond leaves. In addition to N, cover crops influenced the cycling of other nutrients, increasing potassium (K) and boron (B) concentrations while reducing calcium (Ca) and manganese (Mn) in plant tissues. Despite being derived from a two-year study, these results highlight the complexity of interpreting cover crop effects, underscoring the need for further long-term research to provide more comprehensive guidance to growers.

Keywords: organic farming; cover cropping; *Prunus dulcis*; *Lupinus albus*; *Vicia villosa*

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1. Introduction

Portugal has a Mediterranean climate, which is typically conducive to the cultivation of almond trees [1,2]. This plant is well-suited to hot and dry climates, often being grown in rainfed conditions and on poor soils [3–5]. Over the past decade, the area planted with almond trees in Portugal has more than doubled, increasing from 28,480 ha in 2013 to 71,690 ha in 2023 [6].

In Portugal, two main cultivation systems are distinguished. The first is a highly intensive system, characterized by high planting densities (usually above 1000 trees ha^{-1}), fertigation, and a high level of mechanization due to the large plots on which it is established [7,8]. This system predominates in the Alentejo region in the south of the country. In contrast, in the northern regions, cultivated plots are smaller, planting densities are significantly lower (typically less than 400 trees per hectare), fertigation is almost non-existent, and irrigation is rarely used, with most almond orchards being rainfed [7,8]. Under these conditions, productivity tends to be low (~500 kg per hectare), and production cycles are marked by alternate bearing [9]. In the northern region, many producers are drawn to organic farming, where public subsidies provided by the European Union often offset the lower income resulting from reduced productivity.

In organic farming, there are strict restrictions on the use of production inputs, with European Union regulations [10] generally prohibiting the use of synthetic fertilizers and agrochemicals. In the area of plant nutrition, the main constraint to plant growth is the lack of N, which is not present in the soil in forms that can be readily taken up by plants in significant quantities [11]. This issue is exacerbated by the fact that most soils in the region are very shallow and have low levels of organic matter and N reserves [4,12]. Without the option to use industrially synthesized N fertilizers, producers must seek alternatives to introduce N into the soil. One possibility is the use of manure and compost. However, the specialization of agricultural activities and the mechanization of farming practices, especially in arid and semi-arid regions, have led to a reduction in livestock farming and the availability of farmyard manure [11,13]. Therefore, the only rational option for supplying N to crops in organic farming is the use of legumes in cropping systems.

Legumes can establish symbiotic relationships with N-fixing bacteria, commonly known as rhizobia [14]. These symbiotic relationships are the result of millions of years of coevolution and, under suitable conditions, can enable nodulated legumes to obtain all the N they need [15]. In certain circumstances, annual N fixation rates have been observed to exceed 400 kg ha^{-1} [14]. Nodulated legumes use the N acquired from their relationship with these microorganisms for their growth, giving them a competitive advantage over other vegetation in N-poor soils where N is a limiting factor [11].

Moreover, the N resulting from biological fixation, which is contained in the tissues of legumes, can be utilized by non-leguminous species that follow in rotation [16,17] or are grown in intercropping systems [18,19]. This N becomes available to non-legumes primarily after the death and decay of the N-rich legume tissues in the soil. In addition to obtaining N through biological fixation, certain legumes, particularly species within the Lupinus genus, have developed adaptive strategies to access poorly soluble phosphorus (P) pools. These include a suite of morphological, biochemical, and metabolic adaptations that work synergistically to enhance P acquisition [20,21]. Like N, this P can become bioavailable to other vegetation following the degradation and mineralization of legume biomass in the soil [19,22].

In orchards, it is relatively easy to include herbaceous vegetation as a cover crop, since the space between the tree rows is fully available for cultivation. Generally, herbaceous vegetation does not compete with trees for light because it is shorter, but it can compete for water and nutrients [23–25]. If cover crops are composed of legumes, they can offer additional benefits beyond the general advantages of cover crops, such as protecting against soil erosion [26,27] and improving soil organic matter and overall fertility [28,29]. Legume cover crops can provide adequate N levels to the trees, supporting their growth and yield [30]. In the Mediterranean region, many annual herbaceous legumes grow during the winter, coinciding with the tree's resting period. This timing allows for the management of these cover crops with minimal competition for nutrients and water [25,31].

The introduction of legumes as cover crops between orchard rows can involve two different types of vegetation management. One approach is the use of self-reseeding annual legumes, such as subterranean clover, where there is no incorporation into the soil or cutting of the cover crop. Instead, the cover crop is expected to produce seeds and naturally reseed itself in the following year [25,31–33]. These systems offer advantages, particularly on sloped soils where erosion control is important; however, they tend to produce less biomass and fix less N compared to legumes with more vigorous vegetative growth [31] (Rodrigues et al., 2015). Additionally, managing the persistence of the seeded species can be challenging, potentially making the system costly due to the high price of seeds and the need for regular reseeding [31].

Alternatively, annual species with more extensive vegetative growth, such as white lupin and vetch, can be used as cover crops either for incorporation into the soil or to leave on the surface as mulch [28,34,35]. These species produce more biomass, thus fixing more N, and their seeds are generally less expensive. However, natural reseeding is not expected [31,34]. Managing them as mulch is more appropriate when there is a risk of erosion, although N loss through ammonia volatilization can occur [34]. Incorporating these crops into the soil can improve N use efficiency. It also makes the system more vulnerable to erosion, as it requires soil tillage in the spring, a practice known to be a major driver of erosion [26,27,33].

In organic orchards, where N obtained from the Haber-Bosch process cannot be used, employing cover cropping strategies that introduce more N into the system may be a viable approach to ensure better tree nutrition. Following previous studies in conventional olive groves that tested self-reseeding annual legume cover crops [31] and annual legumes managed as mulch [34], this study focused on the use of annual legumes with vigorous vegetative growth—specifically with lupin (*Lupins albus* L.) and hairy vetch (*Vicia villosa* Roth)—with the aim of incorporating them into the soil to improve N use efficiency. The trial was conducted in a young almond orchard organically managed on a gently sloping plot, where the risk of erosion is negligible. The hypothesis is that the use of these legumes could maintain the trees' nutritional status and almond yield at an adequate level while enhancing soil fertility.

2. Materials and Methods

2.1. Site Characterization

The trial was established in a commercial irrigated almond orchard managed under organic farming practices in accordance with European legislation [10]. The orchard is in Alfândega da Fé, northeastern Portugal (41°20′38″ N; 6°56′35″ W; 555 m above sea level).

The almond orchard was planted in 2014 with a 6 × 5 m spacing (333 trees per hectare). The cultivars used were 'Constantí' and 'Vairo,' both grafted onto GF-677 rootstock. For this study, trees from 'Vairo' rows were selected and marked for monitoring of nutritional status and yield assessment.

The region has a typical Mediterranean climate (Csa type), characterized by hot, dry summers and mild, wet winters, with most of the annual precipitation occurring during the winter months [36]. Meteorological data for the trial period are presented in Figure 1.

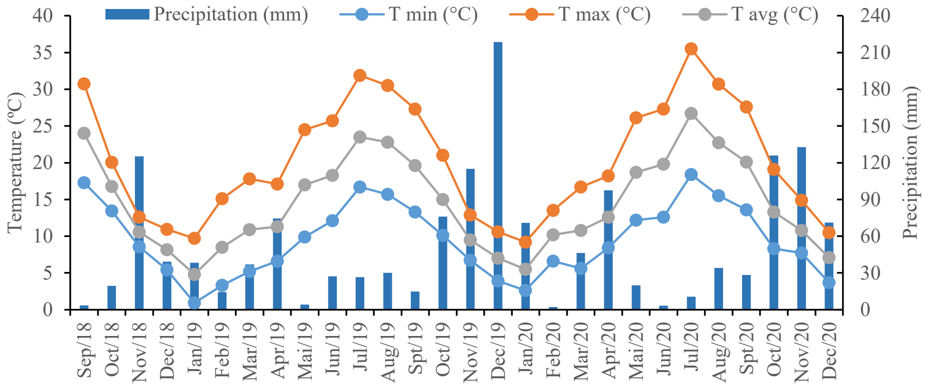

Figure 1. Monthly precipitation and minimum (Tmin), maximum (Tmax), and average (Tavg) air temperatures recorded during the experimental period.

The soil is classified as a Eutric Regosol [37] with a sandy loam texture. Table 1 presents selected chemical properties of the soil, determined in the first year before the start of the experiment, based on three composite samples randomly collected from a depth of 0–0.20 m.

Table 1. Soil properties (mean ± standard deviation) determined before the start of the experiment at the 0–0.20 m depth.

Soil Properties		**Soil Properties (Cont.)**	
[1] Organic C (g kg^{-1})	12.7 ± 4.15	[6] Exchang. Ca (cmolc kg^{-1})	6.7 ± 0.57
[2] pH (H_2O)	6.1 ± 0.32	[6] Exchang. Mg (cmolc kg^{-1})	1.5 ± 0.17
[3] Extract. P (mg kg^{-1}, P_2O_5)	38.5 ± 4.84	[6] Exchang. K (cmol$_c$ kg^{-1})	0.4 ± 0.01
[3] Extract. K (mg kg^{-1}, K_2O)	168.8 ± 50.15	[6] Exchang. Na (cmol$_c$ kg^{-1})	0.2 ± 0.02
[4] Extract. B (mg kg^{-1})	0.3 ± 0.09	[7] CEC (cmol$_c$ kg^{-1})	8.8 ± 0.66
[5] Extract. Fe (mg kg^{-1})	34.0 ± 0.89	[8] Clay (g kg^{-1})	90.6 ± 6.35
[5] Extract. Mn (mg kg^{-1})	16.9 ± 0.12	[8] Silt (g kg^{-1})	163.2 ± 11.73
[5] Extract. Zn (mg kg^{-1})	0.7 ± 0.02	[8] Sand (g kg^{-1})	746.20 ± 5.88
[5] Extract. Cu (mg kg^{-1})	1.7 ± 0.20	Texture (USDA)	Sandy loam

[1] Walkley-Black; [2] Potentiometry; [3] Ammonium lactate; [4] Hot water, azomethine-H; [5] ammonium acetate and EDTA; [6] Ammonium acetate; [7] Cation exchange capacity; [8] Robinson pipette method.

2.2. Experimental Design and Treatment Characterization

The experiment was arranged in a completely randomized design with three treatments and three replicates per treatment. Each experimental unit (replicate) consisted of three adjacent trees within a row. In total, 27 trees were selected, 9 per treatment, all with equivalent canopy volume (Figure 2). For sampling, the three central trees within each experimental unit were selected to ensure representativeness and minimize edge effects.

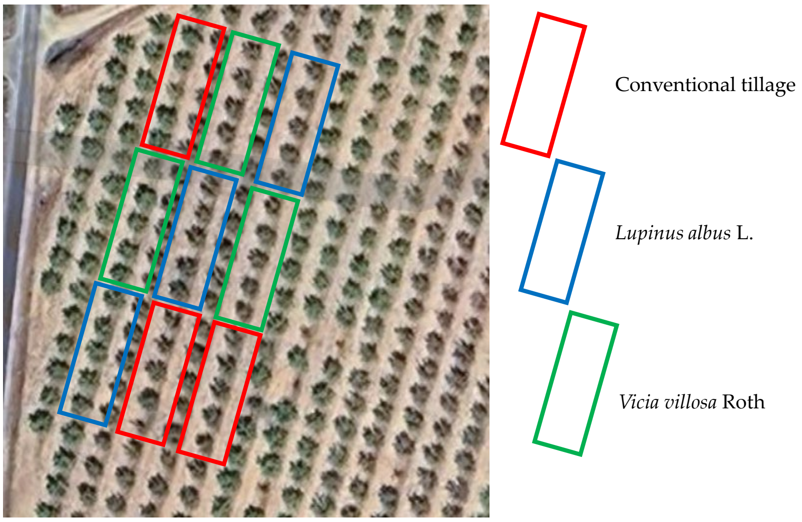

Figure 2. Experimental layout as implemented in the field.

The treatments included conventional tillage as a control. Since the establishment of the orchard, the conventional soil mobilization, the most common soil management practice in the region, has been constantly used and was therefore retained as the control in this study. Two cover crop species were established in the inter-rows: sweet lupin (*Lupinus albus* L.) and common vetch (*Vicia villosa* Roth). Lupin and vetch were sown at seeding rates of 180 and 30 kg ha^{-1}, respectively. Sowing was carried out manually on 10 October 2018, with seeds incorporated into the soil via a shallow cultivation pass. Throughout the study period, the trees were not fertilized to enhance the observable effects of the treatments.

2.3. Plant Tissue and Soil Sampling

On 17 May 2019, before the termination and incorporation of the cover crops into the soil, biomass samples were collected by cutting the plants at ground level using an electric shear and a square frame with 0.5 m sides. The fresh weight of the samples was recorded. Subsamples of approximately 500 g were then taken, weighed again in their fresh state, and transported to the laboratory, where they were dried in a forced-air oven at 70 °C until a constant weight was achieved. The dried subsamples were then ground to pass through a 1 mm mesh for subsequent elemental analysis.

On 11 July and 4 September 2019, and 27 July and 11 September 2020, almond leaf samples were collected to assess the nutritional status of the trees. Mature, fully expanded leaves from the current season's growth were collected from the middle of the shoot and from all quadrants of the canopy, following the international standard protocol for almond leaf sampling [38].

Soil samples were collected on 17 May, 13 June, 27 June, and 31 October 2019, and 7 April 2020, to evaluate N-related indicators and their availability to plants. Composite samples were taken from each experimental unit at a depth of 0–0.20 m, as the soil layers below this depth consist predominantly of coarse materials with limited relevance to tree nutrition. The samples were immediately sieved and dried at 40 °C in a forced-air oven.

On 4 September 2019, and 10 September 2020, fruit harvests were conducted to evaluate yield at the experimental unit level. A trunk shaker equipped with an inverted umbrella was used. After shaking each group of three trees within an experimental unit, the almonds were collected on a tarp laid on the ground and subsequently weighed. Subsamples of approximately 1 kg were taken and separated into their components, kernel, hull, and shell, which were weighed both fresh and after air drying. Each of these components was subsequently oven-dried in a forced-air oven at 70 °C and ground for elemental composition analysis.

2.4. Laboratory Analyses

Cover crop samples were analysed for carbon (C), N, P, K, Ca, magnesium (Mg), B, iron (Fe), copper (Cu), zinc (Zn), and Mn. Other plant tissues, including almond leaves and fruit (kernel, hull, and shell), were analysed for the same elements, except for C, which was not considered relevant for these tissues. C was determined by incineration, N via the Kjeldahl method, B and P by colorimetry, K by flame emission photometry, and Ca, Mg, Cu, Fe, Mn, and Zn by atomic absorption spectrophotometry following sample digestion with nitric acid. Full analytical procedures can be found in Temminghoff and Houba [39].

In the initial soil samples, particle size distribution (clay, silt, and sand fractions) was determined using the Robinson pipette method. Soil pH was measured potentiometrically (soil: solution ratio of 1:2.5), organic C by the Walkley–Black method, extractable P and K using the Egner–Riehm method, and exchangeable bases via ammonium acetate extraction at pH 7. B was quantified by hot-water extraction followed by color development with azomethine-H, and micronutrients (Fe, Cu, Zn, and Mn) were determined using ammonium acetate-EDTA extraction. Detailed procedures for these analyses are described in Van Reeuwijk [40].

Due to the transient nature of inorganic N forms, samples were collected at high frequency (five times throughout the study) to determine soil inorganic N. Soil samples were collected on 17 May, 13 June, 27 June, and 31 October 2019, as well as 7 April 2020. Inorganic

N was extracted from 20 g of soil using 40 mL of 2 M KCl. The suspension was shaken for 1 h and then filtered through Whatman No. 42 filter paper. Nitrate and ammonium concentrations in the extracts were determined using UV–Vis spectrophotometry [41]. For the samples collected on 13 June and 31 October, hydrolysable N was also determined. This followed the same extraction procedure as for inorganic N, but the extracts were incubated in an oven at 100 °C for 4 h prior to analysis. Hydrolyzable N was estimated as the difference between hot and cold extracted inorganic N [13]. For these two sampling dates, total N was also determined using the Kjeldahl method, easily oxidizable organic C was measured by K dichromate digestion, and total organic C was determined by incineration [40].

2.5. Data Analysis

The data were subjected to one-way analysis of variance (ANOVA) after verifying the assumptions of normality and homogeneity of variances using the Shapiro–Wilk and Levene's tests, respectively. When significant treatment effects were detected by ANOVA, mean comparisons were performed using Tukey's Honest Significant Difference (HSD) test at a significance level of $\alpha = 0.05$.

3. Results

3.1. Nutrient Concentration and Recovery in Cover Crop Tissues

Vetch tissues exhibited significantly higher C concentration (543.2 g kg^{-1}) compared to Lupine (530.5 g kg^{-1}). However, no significant differences were observed in the total C accumulated in aboveground biomass due to greater experimental variability (Table 2). In contrast, N concentration was significantly higher in Lupine tissues (29.5 g kg^{-1}) than in Vetch (23.9 g kg^{-1}); however, the total N recovered in aboveground biomass did not differ significantly between the two species (172.5 and 150.7 kg ha^{-1}, respectively), owing to Vetch's slightly higher biomass production. This reflects the concentration/dilution effect, where higher biomass can offset lower nutrient concentrations in plant tissues. No significant differences were detected in P or Mg concentrations in the tissues or in the total amounts recovered in the aboveground biomass. Lupine showed significantly higher Ca concentration (7.7 g kg^{-1}) than Vetch (2.8 g kg^{-1}), and the same occurred in the amount of Ca recovered in aboveground biomass (44.5 vs. 17.1 kg ha^{-1}).

Table 2. Nutrient concentration and recovery (mean ± standard deviation) in the above-ground biomass of lupine and vetch grown as inter-row cover crops.

	Lupine	**Vetch**	**Lupine**	**Vetch**
	Nutrient Concentration		**Nutrient Recovery**	
	g kg^{-1}		**kg ha^{-1}**	
Carbon	530.5 ± 3.5 b	543.2 ± 7.8 a	3118.4 ± 214.3 a	3415.5 ± 356.5 a
Nitrogen	29.5 ± 3.3 a	23.9 ± 2.9 b	172.5 ± 12.0 a	150.7 ± 25.5 a
Phosphorus	2.1 ± 0.7 a	1.6 ± 0.4 a	12.4 ± 3.2 a	9.6 ± 2.1 a
Potassium	23.1 ± 6.7 a	9.3 ± 4.8 b	134.1 ± 32.6 a	56.4 ± 22.6 b
Calcium	7.7 ± 3.0 a	2.8 ± 1.7 b	44.5 ± 15.4 a	17.1 ± 8.2 b
Magnesium	2.5 ± 0.7 a	2.3 ± 0.3 a	14.3 ± 3.2 a	14.6 ± 2.6 a
	mg kg^{-1}		g ha^{-1}	
Boron	16.1 ± 0.7 a	8.4 ± 1.1 b	94.3 ± 2.5 a	52.4 ± 6.7 b
Iron	133.3 ± 14.3 a	92.8 ± 68.5 a	783.9 ± 100.5 a	554.5 ± 345.2 a
Manganese	288.6 ± 112.6 a	43.7 ± 7.8 b	1706.0 ± 710.6 a	271.4 ± 23.8 b
Zinc	27.1 ± 8.1 a	31.6 ± 8.9 a	157.0 ± 40.2 a	200.8 ± 64.8 a
Copper	6.8 ± 1.1 a	8.9 ± 2.3 a	39.6 ± 5.4 a	56.3 ± 16.5 a

Means followed by the same letter in columns are not significantly different by the Tukey HSD test ($\alpha = 0.05$).

Among the micronutrients, Lupine displayed higher tissue B concentration (16.1 mg kg^{-1}) than Vetch (8.4 mg kg^{-1}), which translated into greater total B recovery in aboveground biomass (94.3 vs. 52.4 g ha^{-1}) (Table 2). No significant differences were observed between species in the concentrations or recoveries of Fe, Zn, and Cu. However, Mn concentration was markedly higher in Lupine tissues (288.6 mg kg^{-1}) compared to Vetch (43.7 mg kg^{-1}), with significant differences also persisting in the amount of Mn recovered in aboveground biomass (1706.0 vs. 271.4 g ha^{-1}).

3.2. Nutrient Concentration in Leaves and Almonds, and Almond Yield

Leaf analyses revealed a consistent trend of lower N concentrations in the Control treatment compared to the cover crop treatments (Figure 3). P concentrations did not vary significantly among treatments. K levels in leaves showed a marked decline in the Control treatment during the September 2019 sampling, coinciding with fruit harvest in the first year. Vetch consistently exhibited higher K concentrations across all sampling dates.

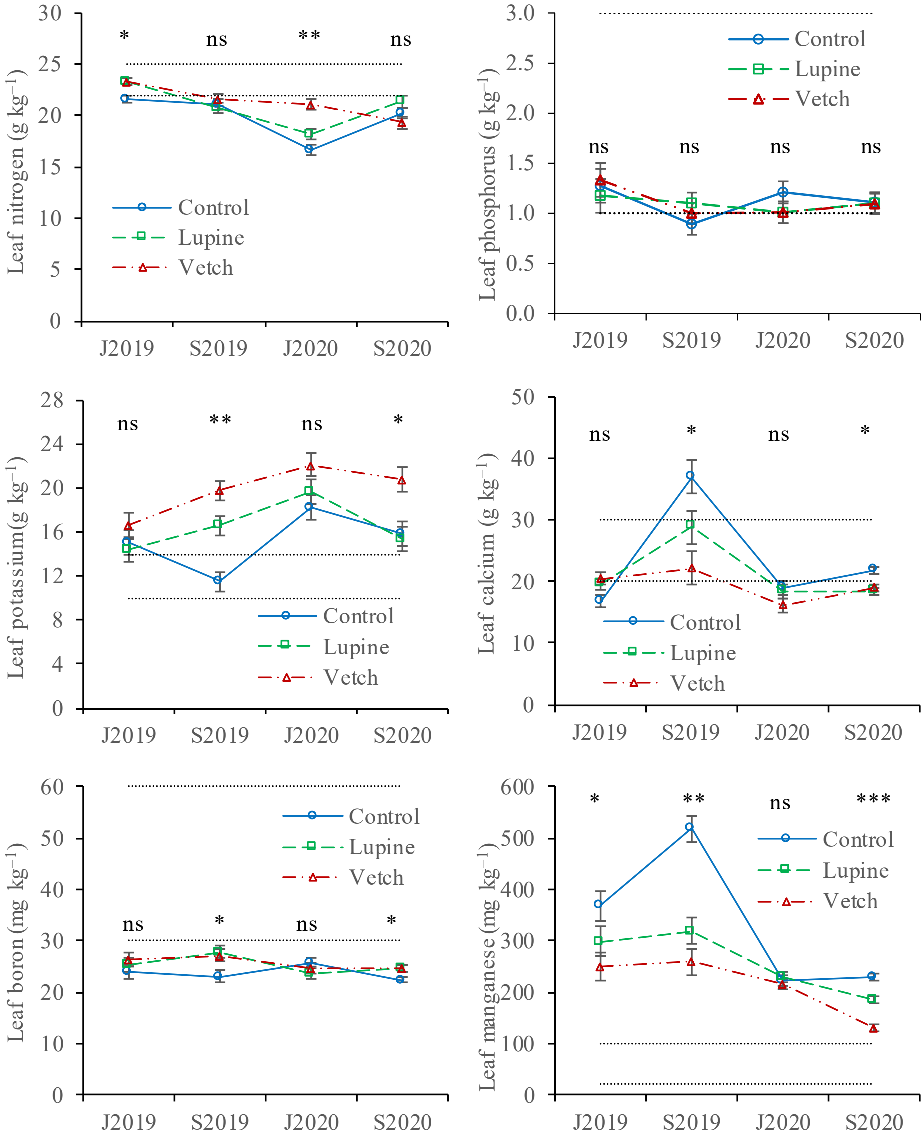

Figure 3. Leaf concentrations of macro- and micro-nutrients as affected by treatments: Control (soil tillage) and inter-row cultivation of Lupine and Vetch as cover crops, across sampling dates (J = July; S = September). Significant differences are indicated as * ($\alpha < 0.05$), ** ($\alpha < 0.01$), and *** ($\alpha < 0.001$); ns denotes no significant difference between treatments. Error bars represent standard errors. Dashed lines define the sufficiency ranges, following Bryson et al. [38].

Ca concentrations in leaves peaked in the Control treatment, particularly during the September 2019 sampling, with values notably higher than those observed in the cover crop treatments. B concentrations tended to be higher in treatments with cover crops compared to the Control, with significantly elevated values in the September samplings.

In contrast, Mn concentrations were higher in the Control treatment, with three sampling dates showing statistically significant differences compared to the other treatments. No significant differences were observed among treatments for the remaining nutrients analyzed: Mg, Fe, Zn, and Cu.

In 2019, kernel yield was significantly higher in the Control treatment (404 kg ha^{-1}) compared to Lupine (246 kg ha^{-1}) and Vetch (283 kg ha^{-1}) (Figure 4). However, in 2020, this pattern was reversed, with the Control treatment recording significantly lower yields (199 kg ha^{-1}) than both Lupine (313 kg ha^{-1}) and Vetch (296 kg ha^{-1}).

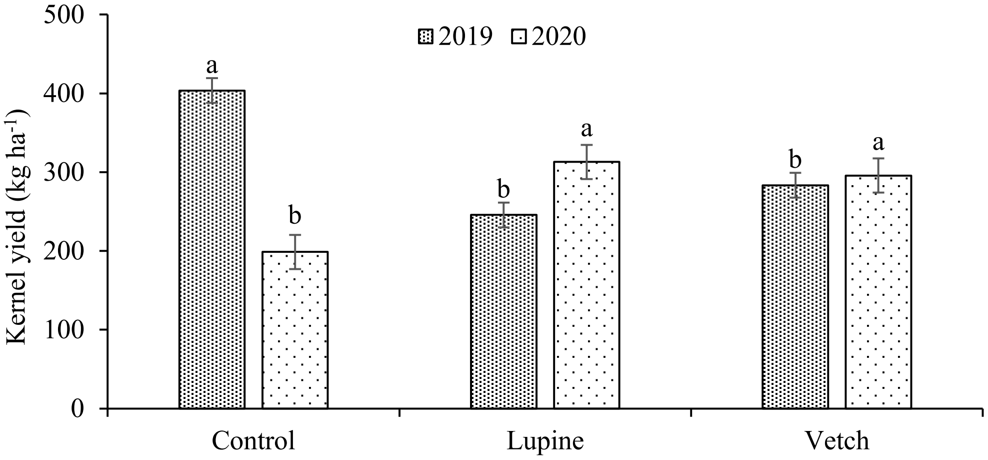

Figure 4. Kernel yield as affected by treatments: Control (soil tillage) and inter-row cultivation of Lupine and Vetch as cover crops. Means followed by the same letter are not significantly different according to the Tukey HSD test (α = 0.05). Error bars represent standard errors.

In 2019, total N content in the different fruit parts varied significantly in the kernel and hull but not in the shell (Figure 5). Consequently, due primarily to differences in kernel and hull N, the total N content in the fruits also differed significantly among treatments. Overall, the Control treatment exhibited significantly higher N levels compared to the Lupine and Vetch treatments.

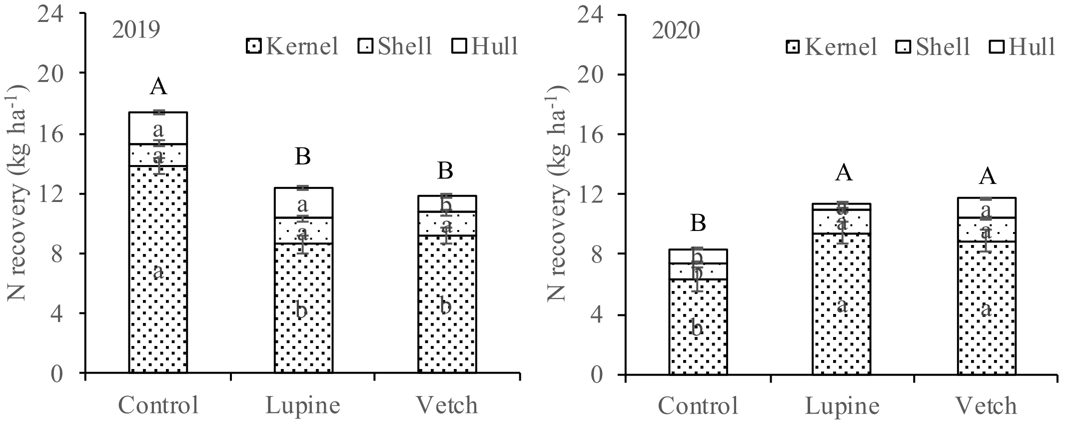

Figure 5. *Cont.*

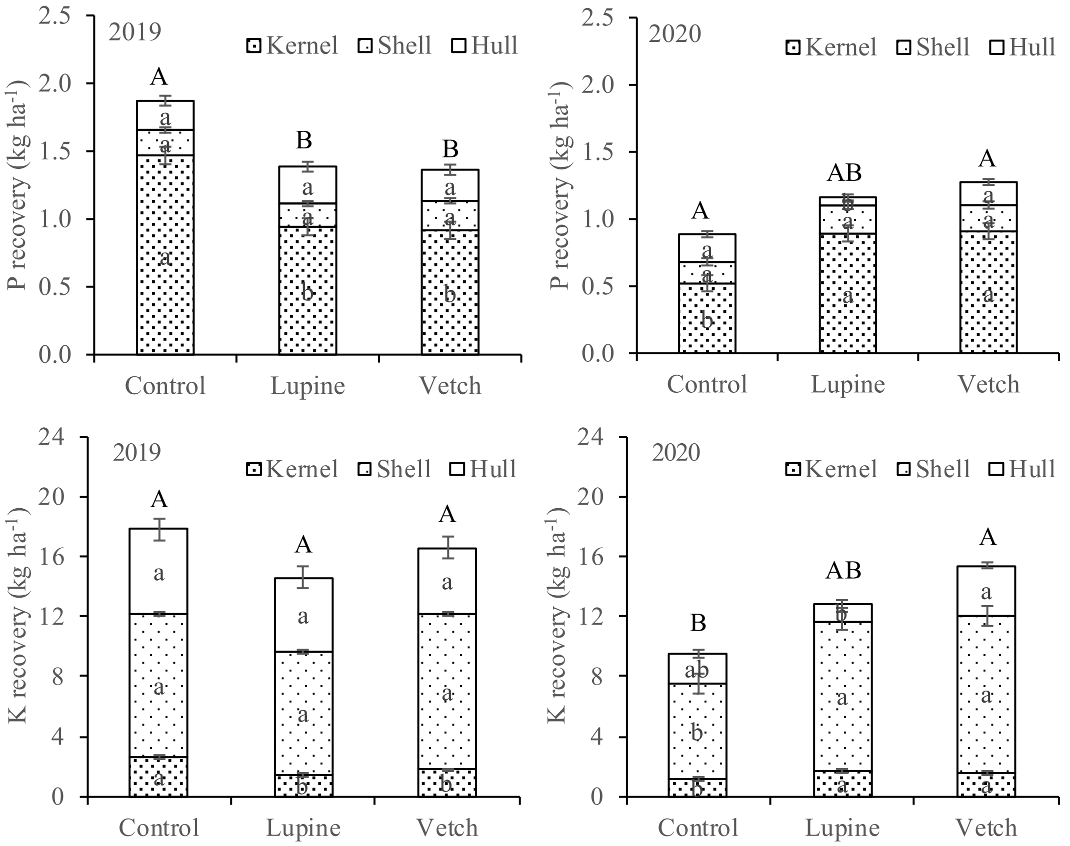

Figure 5. Recovery of nitrogen (N), phosphorus (P), and potassium (K) in different fruit parts (kernel, shell, and hull) and total, in 2019 and 2020, as affected by treatments: Control (soil tillage) and inter-row cultivation of Lupine and Vetch as cover crops. Means followed by the same letter (lowercase for fruit parts; uppercase for total) are not significantly different according to the Tukey HSD test (α = 0.05). Vertical bars represent standard errors.

In 2020, the opposite trend was generally observed, with the Control treatment showing lower N contents in the fruits and their respective components compared to the cover crop treatments. P content in the fruit tissues followed the same pattern as N, with similar trends observed in both years.

For K, no significant differences were observed in the total amount contained in the fruits during the first year. However, in the second year, K content followed a pattern similar to that of N and P, with lower average values in the Control treatment, although the difference was not statistically significant when compared to Lupine.

3.3. Indicators of Soil Nitrogen Availability

On 13 June 2019, the cover crop treatments exhibited significantly higher soil Kjeldahl N concentrations compared to the Control (Table 3). A similar trend was observed for both permanganate-oxidizable C (i.e., easily oxidizable C) and total organic C. By 31 October 2019, soil N and total organic C levels remained significantly lower in the Control plots than in those receiving cover crops. However, by this date, no significant differences among treatments were detected for easily oxidizable C.

Soil ammonium levels remained low during May and June, beginning to increase in autumn with the onset of rainfall and decreasing temperatures (Figure 6). Nitrate levels showed an upward trend starting in May, also peaking in autumn before subsequently declining. On the three intermediate sampling dates, soil nitrate levels were significantly lower in the Control treatment compared to the Lupine and Vetch treatments.

Table 3. Kjeldahl nitrogen (N), easily oxidizable organic carbon (EOC), and total organic C (TOC) (mean ± standard deviation) in soil samples collected at 0–20 cm depth on 13 June and 31 October 2019, as affected by treatments: Control (soil tillage) and inter-row cultivation of Lupine and Vetch as cover crops.

	13 June 2019			31 October 2019		
	N Kjeldahl	EOC g kg^{-1}	TOC	N Kjeldahl	EOC g kg^{-1}	TOC
Control	1.0 ± 0.09 b	17.6 ± 0.48 b	20.1 ± 2.30 b	1.1 ± 0.10 b	23.2 ± 0.67 a	24.5 ± 1.62 b
Lupine	1.3 ± 0.10 a	22.4 ± 1.25 a	25.3 ± 0.73 a	1.6 ± 0.07 a	24.2 ± 0.79 a	27.7 ± 1.31 a
Vetch	1.3 ± 0.03 a	22.0 ± 1.19 a	26.0 ± 1.80 a	1.5 ± 0.09 a	24.0 ± 0.44 a	27.6 ± 0.88 a

Means followed by the same letter in columns are not significantly different by the Tukey HSD test (α = 0.05).

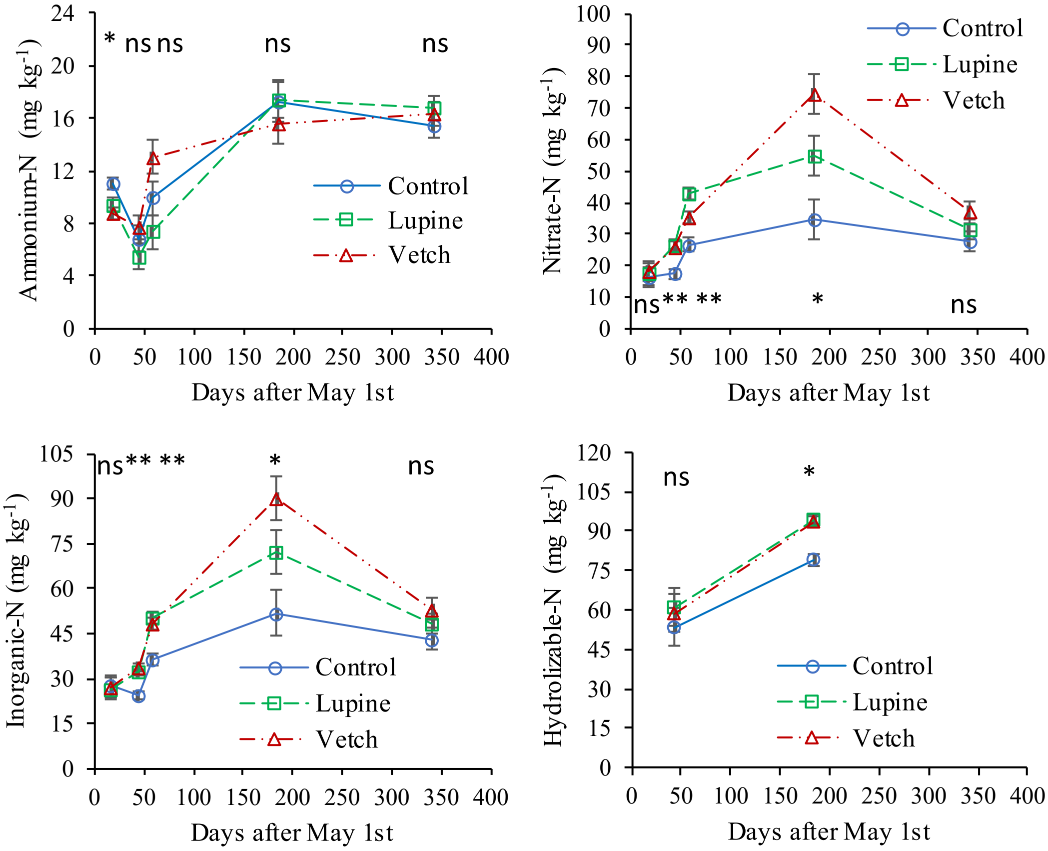

Figure 6. Inorganic and hydrolysable nitrogen (N) in the soil (0–20 cm) as affected by treatments: Control (soil tillage) and inter-row cultivation of Lupine and Vetch as cover crops. Inorganic N was measured in five sampling dates (17 May 2019, to 7 April 2020), and hydrolysable N was determined on two dates (13 June and 31 October 2019). Data were converted to a continuous variable starting from May 1 for improved graphical visualization. Significant differences are indicated as * ($\alpha < 0.05$), and ** ($\alpha < 0.01$); ns denotes no significant difference between treatments. Error bars represent standard errors.

Mineral inorganic N, calculated as the sum of nitrate and ammonium, followed the same pattern as nitrate due to its quantitatively higher contribution. Hydrolysable N did not differ significantly among treatments the first time it was measured, on the second sampling date, 13 June, but showed significant differences at the second measurement on 31 October, with the Control treatment displaying lower values than the cover crop plots.

4. Discussion

Almond yield was higher in the control treatment during the first year and in the cover crop treatments in the second year. These cover crops are highly competitive, producing substantial biomass and remaining in active growth until late spring [42]. Conversely, almond trees are characterized by very early flowering, and by June, the yield for the current year is already determined [2]. The lower productivity of almond trees under cover cropping in the first year, compared to the control, is likely attributable to competition between the herbaceous vegetation and the trees, particularly for water. It should be noted that the winter and spring of that year were particularly dry (Figure 1). Several other studies assessing yield have shown that cover crops can reduce orchard productivity [19,24,28]. In viticulture, some studies even suggest that the use of cover crops may reduce vine vigor, which can be beneficial for grape quality [23]. On the other hand, the pronounced interannual fluctuations in Mediterranean rainfall present a persistent challenge for perennial species, undermining their ability to maintain stable yields [2,4,19].

In the second year, however, the relative performance reversed, with the cover crop treatments resulting in higher fruit production. Two factors may have contributed to this outcome: the phenomenon of alternate bearing and the beneficial effect of leguminous cover crops on plant N nutrition. Alternate bearing is typical of Mediterranean fruit trees, wherein an on-year is invariably followed by an off-year [43,44].

Attempts to explain the alternate bearing habit in Mediterranean fruit species have focused on hormonal influences exerted by developing seeds in the current year on the floral induction of buds that would bloom in the following year [43,45]. An equally plausible explanation considers the competition for photosynthates between reproductive structures (flowers and fruits) and the vegetative growth of current-year shoots. In this context, reproductive organs act as primary sinks for photosynthates in trees, thereby limiting vegetative development [46–48]. However, overall productivity levels were not particularly high, which may weaken the alternate bearing hypothesis, as the phenomenon tends to be more pronounced following years of either very high or very low yields [19].

Nutritional factors may have played a significant role. On the one hand, the trial was conducted in an organically managed orchard. Leaf N concentrations were low when compared to the established sufficiency range for this crop [38], indicating a N deficiency condition. On the other hand, trees in the plots with cover crops exhibited higher N levels than those in the control treatment, a factor that may underlie the observed increase in productivity, particularly considering the well-documented role of N in enhancing overall plant performance [11,49] and in almond trees specifically, as previously reported in earlier studies [4,50].

Various studies have indicated that legumes can accumulate very high amounts of N in their tissues [42,51], owing to their capacity to establish symbiotic relationships with N-fixing microorganisms and, through this mechanism, gain access to atmospheric N [14]. The results of this study also revealed higher soil N indicators in the plots with cover crops compared to the control, which corresponded with higher leaf N concentrations in the almond trees in those same plots. Legumes are widely used in agriculture as green manures, as their N-rich tissues are incorporated into the soil, initially increasing total soil N content. This N is gradually mineralized over time and can subsequently be taken up by companion species, such as fruit trees [25,30,31] or herbaceous crops grown in succession as part of a rotation system [52,53]. In the context of this study, the supplemental N in the plots with cover crops is likely the principal factor underlying the increased almond productivity observed in the second year.

No effect of the treatments on leaf P concentration was observed. Legumes, particularly white lupin, are known to access sparingly soluble P in the soil through a range of morphological, biochemical, and metabolic adaptations that collectively enhance P acquisition [20,21]. Once incorporated into the soil, the P-enriched tissues of legumes undergo mineralization through the action of phosphatases, potentially making P available to subsequent crops [20,54]. In this case, however, no effect was detected in the almond leaf tissue, likely due to a dilution effect caused by the large canopy size, which may have masked any increase in P concentration. Additionally, P is characterized by low mobility in the soil, as it tends to strongly bind with cations, such as Ca, Fe, and aluminum (Al), thereby reducing its immediate availability to plants [55].

K concentrations in almond leaves tended to be lower in the control treatment than in the plots with cover crops, whereas Ca concentrations followed the opposite trend. It is plausible that K absorbed by the legumes became rapidly available to the almond tree roots, as K does not form part of organic structures [49]. Once plant cells die and their structures disintegrate, K is released into the soil solution as a cation without requiring microbial mineralization, making it readily available for uptake by tree roots, potentially in quantities sufficient to produce significant differences between treatments. Ca, on the other hand, is largely associated with cell membranes and walls [49]. Therefore, it takes longer to become available again for plant absorption. This characteristic, combined with the ionic antagonism often observed between K and Ca [11], likely contributed to the reduced Ca concentrations in the almond leaves from the cover crop plots compared to the control. Nevertheless, these nutrients are unlikely to have played a decisive role in the trees' nutrition, as their concentrations in the leaves were either above or within the sufficiency range for almond [38].

B concentrations tended to be lower in the almond leaves of the control treatment compared to those in the cover crop treatments. Although, like Ca, a portion of B is also bound to cell walls [56], dicot plants generally contain higher levels of B in their tissues [56,57]. This characteristic may have facilitated nutrient uptake in the cover crop treatments, especially since antagonistic interactions were unlikely to have occurred in this case. Overall, B levels in the leaves were below the sufficiency range established for the crop [38], a condition frequently observed in the region for other fruit tree species [58,59], as well as for almond [4,60]. These suboptimal tissue B levels may have accentuated the emergence of significant differences among treatments.

Leaf Mn concentrations tended to be higher in the control treatment compared to the cover crop treatments. In this region, crops grown in these acidic soils commonly exhibit elevated Mn levels in their tissues [12,61]. The presence of legumes appeared to reduce Mn concentrations in almond leaves, possibly due to competition for the nutrient. Additionally, soil aeration is a factor known to increase Mn availability [62,63]. In this study, the legumes may have enhanced soil aeration by absorbing water, thereby contributing to the reduction in Mn concentrations in the almond leaves. Higher levels of organic substrate in the soil tend to promote the presence of humic and fulvic acids, which, in turn, can complex Mn^{2+} ions, forming less soluble or less bioavailable compounds [11]. In this context, the residues left in the soil by the legumes likely reduced Mn uptake through chelation of the metal. This outcome may indicate a beneficial effect of introducing cover crops, given that Mn concentrations in the plant tissues were well above the established sufficiency range for almond, potentially indicating a situation of toxicity [38,57,64].

5. Conclusions

The introduction of legume cover crops appears to have reduced almond yield in the first year, likely due to competition between the herbaceous vegetation and the trees for essential resources. In the second year, however, the trend was reversed, with higher yields observed in the cover crop treatments, possibly because of the release of key nutrients such as N. The results also revealed significant variation in the concentrations of other nutrients in plant tissues, indicating that legume cover crops used as green manures may influence the cycling of numerous nutrients beyond N. In this study, legume cover crops contributed to increased tissue concentrations of K and B while reducing Ca availability. Additionally, they favorably decreased Mn concentrations in the plant tissues. These findings suggest that long-term studies should be conducted to generate more robust data that can support informed decision-making and be effectively disseminated among farmers.

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