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Ground Management Through Grazing in Rainfed Olive Orchards Provides High Olive Yields and Has Other Potential Benefits for Both the Soil and the Farmer

Paulo Dimande [1,2], Margarida Arrobas [2,3], Carlos M. Correia [4] and Manuel Ângelo Rodrigues [2,3,*]

1 Escola Superior de Desenvolvimento Rural, Universidade Eduardo Mondlane, Bairro 5º Congresso, VilanKulos 1304, Mozambique; paulo.j.dimande@uem.mz
2 Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal; marrobas@ipb.pt
3 Laboratório para a Sustentabilidade e Tecnologia em Regiões de Montanha, Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal
4 Centre for the Research and Technology of Agro-Environmental and Biological Sciences (CITAB), University of Trás-os-Montes and Alto Douro, 5001-801 Vila Real, Portugal; ccorreia@utad.pt
* Correspondence: angelor@ipb.pt

Abstract: Soil management in orchards can have several economic and environmental implications. In this study, three different soil management systems were compared in a dry-farmed olive grove: conventional tillage (tillage), glyphosate-based herbicide (herbicide) and sheep grazing. The experiment lasted eleven years (2011–2022) and was carried out after a previous trial conducted on the same plot with the same treatments and duration (2001–2011). However, in the earlier trial, the herbicide and sheep grazing treatments switched positions in the plot, while the tillage treatment remained in its original place. The average total accumulated olive yields between 2011 and 2022 were 225.1, 230.9, and 245.0 kg tree^{-1} for the sheep grazing, tillage, and herbicide treatments, respectively. However, no significant differences were observed between the treatments. The levels of total organic carbon in the soil, measured in samples collected in the last year of the study, were 41.3, 33.7, and 37.3 g kg^{-1}, respectively, for the same treatments. These findings indicated that the tillage treatment exhibited lower soil organic matter content and reduced bioavailability of some nutrients, which raises concerns about its sustainability. On the contrary, employing sheep grazing with an appropriate stocking rate, effectively controlling vegetation in the spring, ensured favourable soil properties and olive yields comparable to the other treatments. Moreover, the sheep grazing approach provides supplementary advantages to the farmer, including revenue from the sale of animal products and the opportunity to transition to organic farming systems, which better align with the preferences of contemporary societies.

Keywords: soil management; cover cropping; *Olea europaea*; mixed farming; organic farming; regenerative agriculture

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1. Introduction

Soil management in fruit growing remains a topic of lively debate, particularly within the organic farming movements, which advocate against soil tillage and consistently recommend cover cropping [1–3]. However, soil management strategies cannot be separated from local agro-environmental variables [4,5]. In regions characterized by a Mediterranean climate, with high rainfall erosivity and sloping terrain, maintaining year-round vegetation cover is essential to prevent soil erosion [6,7]. In rainfed fruit cultivation within arid and semi-arid regions, as well as in shallow soils with reduced organic matter content and low water holding capacity, there might be a necessity to limit the growth of herbaceous vegetation due to the risk of excessive competition for water. Despite cover cropping strategies being recommended by scholars for orchards over the years, this could be a significant reason why many farmers in the Mediterranean basin persist in tilling the soil of their rainfed managed orchards [5,8,9].

The use of herbicides remains a popular option among farmers. Despite global ecological concerns regarding the excessive use of pesticides in agriculture [2,10,11], various herbicidal molecules continue to be authorized for olive growing and are commonly employed by farmers. Herbicides are favoured for their high effectiveness in controlling weeds, particularly in the initial years of application, and are widely utilized in perennial crops. In regions with wet climates or irrigated orchards, the predominant soil management system involves herbicide application within the rows and cover cropping in the interrow [5,12]. The use of herbicides across the entire soil surface of orchards as the primary method of weed control remains prevalent [1,11], particularly in rainfed orchards situated in arid and semi-arid regions [5,8,9,13]. Commercial herbicides may contain residual, post-emergence, or a combination of both components [14].

Cover cropping is widely regarded as the most recommended strategy in academic and scientific circles. Its primary advantages include protecting the soil against erosion [6,7] and enhancing soil organic matter as well as various physical, chemical, and biological soil properties [4,15,16]. However, there is a concern that cover crops may potentially lead to excessive competition for water, thereby reducing crop growth and yield [5,8,12,17]. Furthermore, there is a diverse range of methods for implementing cover cropping. It can involve managing weeds or sowing vegetation. In the latter case, the approach may involve using a single species or biodiverse mixtures containing different botanical groups with varying growth habits and biological cycles, depending on the specific objectives intended for the orchard. Methods for managing cover crops can also vary, including mechanical mowing, grazing, or cutting vegetation and leaving it on the ground as mulch [3–5,8,18,19].

In 2001, a study of soil management in a rainfed olive orchard began in Bragança, in the northeast of Portugal. Three treatments were tested: soil tillage, the most commonly used soil management system in the region at the time; post-emergence herbicide, representing the primary alternative followed by farmers; and sheep grazing, a plot with natural vegetation managed through grazing. The results obtained in the first 11 years, until the 2011 harvest, have already been published [8]. These initial findings indicated that the plot managed with herbicide was the most productive (187.2 kg tree^{-1}), followed by soil tillage (142.9 kg tree^{-1}) and sheep grazing (89.5 kg tree^{-1}). The significantly lower result in the grazed plot was attributed to insufficient control of vegetation during spring (April–June). During this period, soil moisture and temperature are highly conducive to plant growth, leading to inadequate grazing of the vegetation. Additionally, spring marks the transition to the dry season, characterized by minimal rainfall in the subsequent months. Consequently, the herbaceous vegetation, left largely ungrazed by animals, continues to transpire soil water, which will no longer be replenished by precipitation. This leaves the trees in this plot in a less favourable water condition to withstand the hot and dry summer compared to those in other plots.

After observing seemingly clear and insightful results during the initial 11 years, changes were made to the experimental design starting from 2012. These changes involved altering the management of vegetation on the grazed plot and the plot previously managed with herbicide, effectively swapping their management methods. The tilled plot remained unchanged and served as the control treatment. Additionally, the stocking rate was increased during spring, concentrating the herd in the grazed plot to the detriment of other areas on the farm. Given the importance of increasing the number of animals in farms dedicated to perennial woody crops, which is increasingly demanded in organic farming systems such as regenerative agriculture, and the near-total absence of studies on cover cropping in woody species that include animals, this study is of particular significance. It can fill a knowledge gap by evaluating the effect of cover crop management with grazing on olive production. Our previous study demonstrated that grazing, compared to more effective vegetation control methods, can reduce olive yield, deterring farmers from adopting it. This study aims to address this issue by adjusting the stocking rate to simultaneously enable livestock production and maintain tree productivity.

Thus, this new study was conducted for another 11 years, until the 2022 harvest, with the new working hypothesis: cover crops can be effectively managed by grazing if an adequate stocking rate is used.

2. Materials and Methods

2.1. General Experimental Conditions

The field experiment was conducted in a 50-year-old olive orchard of cultivar Cobrançosa, located in Bragança (41°48′ N; 6°44′ W) in northeast Portugal. The region's climate is typically Mediterranean with some influence from the Atlantic regime. According to the Köppen classification, Bragança experiences a Csb climate, characterized by dry and warm summers and rainy winters [20]. The average annual precipitation and temperature are 741 mm and 11.9 °C, respectively. The monthly variation in precipitation and temperature is shown in Figure 1. The soil is classified as an Eutric Regosol [21] with a sandy loam texture (128, 326, and 546 g kg^{-1} of clay, silt, and sand, respectively). When the original study began in 2001, the soil organic carbon (C) content was 5.8 g kg^{-1}, and the pH (soil water, 1:2.5) was 6.0.

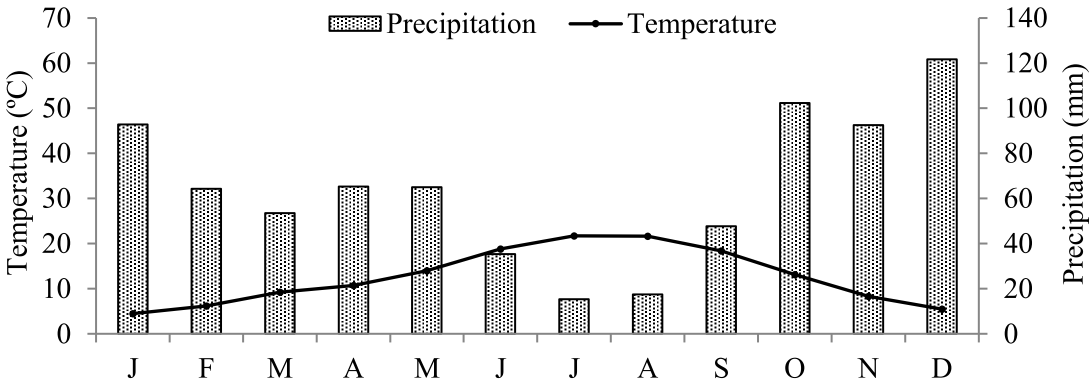

Figure 1. Average (1981–2010) monthly precipitation and temperature in Bragança [20].

2.2. Treatments and Field Plot Management

As mentioned earlier, a previous study in the same orchard commenced in 2001. At the onset of the study, three treatments were established: (i) sheep grazing, where the plot was managed with a flock of sheep and goats; (ii) tillage, involving two tillage passes per year in spring using a cultivator; and (iii) glyphosate, a non-selective glyphosate-based herbicide (360 g L^{-1} of active ingredient; applied once a year in April at a rate of 4 L ha^{-1} of herbicide). A group of ten trees of similar canopy size was marked in each treatment. All three plots received equal amounts of fertilizers, namely, 1.5 kg tree^{-1} yr^{-1} of compound fertilizer (10% N, P_2O_5, and K_2O) and 7.7 g tree^{-1} yr^{-1} of boron (B) as borax. The results obtained in the first 11 years, until 2011, have already been published [8].

In 2012, changes were made to the experimental design. The sheep grazing treatment was swapped with the glyphosate plot, while the tillage treatment remained in the same plot as a control. Additionally, the grazing regime in the sheep grazing treatment was readjusted. Initially, in the first cycle of this study, a flock of 90–100 sheep and goats grazed an area of 12 ha, which included the sheep grazing plot and meadows. This represented an annual stocking rate close to 1.2 livestock units per hectare. Approximately 5 ha of meadow were not grazed from April to June to allow for hay production. In the second study cycle, the herd concentrated on the experimental sheep grazing plot between April and June, aiming for more effective vegetation control, which allowed for an additional hectare to be left for hay production. Regarding the tillage plot, it began to be managed with just one cultivator pass per year instead of two, as was carried out in the initial study.

Tree pruning in this second cycle was conducted annually, with no more than 10 to 15% of the canopy volume being removed to maintain the uniform volume of the trees. All other cropping practices remained the same as in the first cycle of the study [8].

2.3. Leaf and Soil Sampling and Crop Harvest

At the beginning of the study, composite soil samples were collected to perform a comprehensive characterization of the plot, including analysis of soil properties such as pH, organic matter content, and nutrient levels. Soil sampling was repeated at the end of the trial, specifically on 17 February 2023, to assess the effect of the treatments on soil properties. Sufficient soil was collected during this sampling to conduct a pot experiment aimed at determining biological indices of soil nutrient availability. Soil samples were collected from a depth of 0–0.20 m, sieved using a 2 mm mesh, and subsequently oven-dried at 40 °C.

Leaf samples were collected from the middle third of one-year-old shoots, covering the entire canopy, twice a year: once during the tree's resting period in January and again in summer during endocarp sclerification in July. In the laboratory, the leaves were subjected to oven-drying at 70 °C and then ground using a 1 mm mesh.

The olives were harvested in late autumn using a trunk-shaker machine. Panels were placed on the ground beneath the trees to collect the fruits as they were shaken off. The harvested olives were weighed separately for each tree. In 2019 and 2021, 30 fruits were randomly selected for biometric measurements and elemental composition determination of the pulp and pit.

2.4. Pot Experiment

The pot experiment was designed to obtain a biological indicator of nutrient availability in the soil and to complement the data obtained from direct soil sample analyses. Therefore, the pot trial was conducted at the end of the study to better highlight the effects of treatments on soil quality. The pot experiment started on 19 April 2023. Soil samples were collected from the canopy projection area of each of the 30 marked trees. The pots were placed outdoors for two months and watered regularly as needed, depending on environmental conditions and vegetation growth. After harvesting the biomass, it was oven-dried at 70 °C, weighed, and ground.

2.5. Laboratory Analyses

Soil analyses included pH (H_2O and KCl, soil:solution, 1:2.5), cation-exchange capacity (ammonium acetate, pH 7.0), easily oxidizable C (wet digestion, Walkley–Black), total organic C (incineration), extractable phosphorus (P) and potassium (K) (the Egnér–Riehm method), extractable B (hot water and azomethine-H method) and soil texture (the Robinson pipette method). For detailed analytical procedures, readers are referred to Van Reeuwijk [22]. Additionally, the availability of other micronutrients [copper (Cu), iron (Fe), zinc (Zn), and manganese (Mn)] in the soil was determined by atomic absorption spectrometry after extraction with DTPA (diethylenetriaminepentaacetic acid) buffered at pH 7.3, following the standard procedure of FAO [23].

Tissue samples (olive leaves, pulp, pit, and ryegrass tissue) were analysed for nutrient concentration after digestion with nitric acid in a microwave. Elemental analyses were conducted using the Kjeldahl method for nitrogen (N), colorimetry for B and P, and atomic absorption spectrophotometry for K, calcium (Ca), magnesium (Mg), Fe, Mn, Cu, and Zn methods [24].

2.6. Data Analysis

The results were analysed using the statistical software SPSS Statistics (v. 25, IBM SPSS Armonk, NY, USA). The assumptions of normality and homogeneity were verified using the Shapiro–Wilk and Levene tests, respectively, before performing the one-way ANOVA. When significant differences were found, means were separated using the post hoc Tukey HSD test (α = 0.05).

3. Results

3.1. Olive Yield and Alternate Bearing Cycles

The results of the eleven harvests, from 2012 to 2022, are shown in Figure 2. The year-to-year variation in olive yield appears to be consistent across all treatments, suggesting that it is likely dependent on other agro-environmental variables rather than the soil management system alone. The cumulative olive yields were 245, 231, and 225 kg tree^{-1} in the herbicide, tillage and sheep grazing treatments, respectively, with no significant differences observed between treatments (p = 0.6937). Furthermore, the analysis of variance for the olive yield results of each individual year also did not show significant differences between treatments.

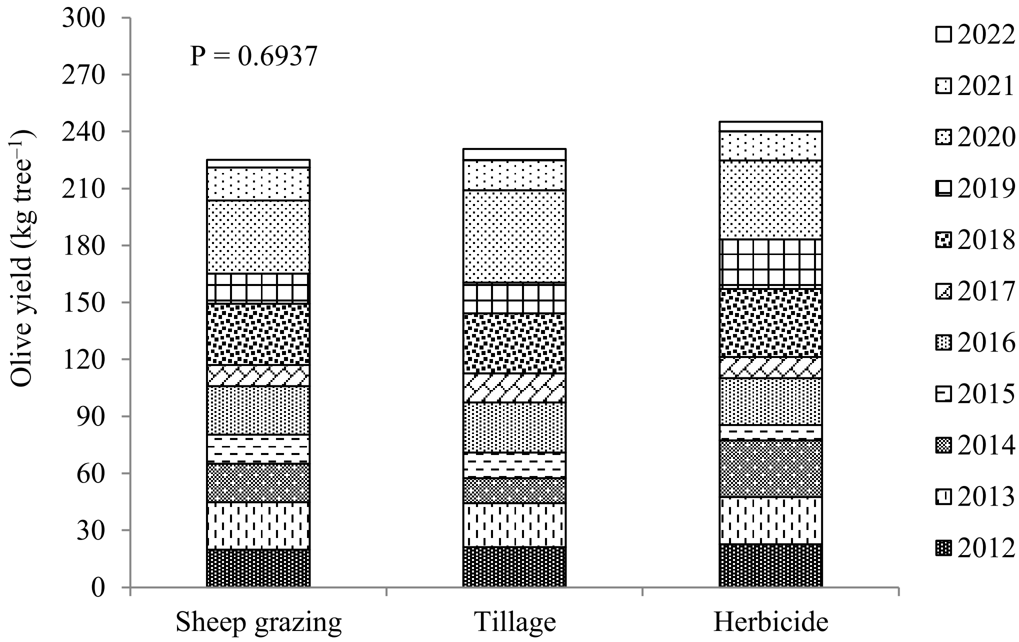

Figure 2. Annual olive yields from 2012 to 2022 as a function of soil management treatment. p is the probability of the accumulated olive yields (2012–2022).

Figure 3 displays the olive yield of the thirty trees in the trial, irrespective of the soil management treatment, in an attempt to provide greater visibility to the alternate bearing cycles. The figure depicts a collective trend, but at times, it is not consistently followed by all individual trees, suggesting various interactions among the agro-environmental factors that determine productivity in an olive orchard.

3.2. Tree Nutritional Status

Leaf N concentration varied significantly between treatments on 8 out of the 22 sampling dates (Figure 4). A consistent trend for higher values in the herbicide treatment, particularly in the initial years of the experimental period, was observed. Additionally, considerable fluctuation was recorded among sampling dates in leaf N concentration values, indicating other relevant factors contributing to variation besides the treatment effects.

Leaf P concentration varied significantly with treatments in 8 out of 22 sampling dates (Figure 4). However, the pattern of variation differed from that of N. Except for the initial sampling dates, where the variation seemed similar to that of N, with higher values in the herbicide treatment (W12 and W13); in subsequent years, the variation in tissue P concentration did not appear to be related to the treatment effects.

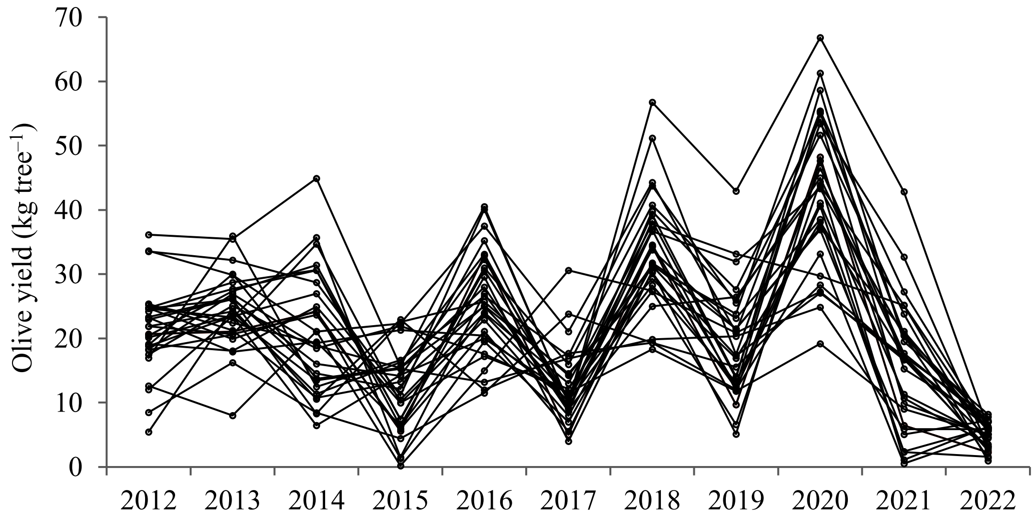

Figure 3. Olive yields of the thirty individual trees in the trial over the course of the eleven harvests.

The leaf K concentration did not exhibit a consistent relationship with the treatments, although significant differences between treatments were observed in 5 out of 22 samplings (Figure 4). In the K values, what stands out is a significant fluctuation among sampling dates, with a strong tendency for higher values in summer samplings compared to samplings during the resting period of olive.

The Ca concentration in the leaves exhibited a pattern similar to that of K, with no consistent differences between treatments and showing significant variation among sampling dates (Figure 4). However, while K values showed a strong tendency to be higher in summer samplings, leaf Ca concentrations tended to be higher in winter samplings. On the other hand, leaf Mg concentrations fluctuated less than those of Ca among sampling dates but showed a similar trend, with values tending to be higher in samplings during vegetative rest.

The leaf concentrations of the micronutrients B, Fe, Mn, Zn, and Cu did not exhibit a clear relationship with the soil management treatments and were provided as Supplementary Materials (Figure S1). B concentration in the tissues consistently varied over the years among sampling dates, with values tending to be higher in summer samplings, following the K trend. The other micronutrients showed inconsistent variation with both treatments and sampling dates, suggesting that they may depend on agro-environmental variables not considered in this study.

The attempt to assess the effect of treatments based on fruit size and pulp/pit ratio or nutrient concentration in the pulp and pit was not greatly informative, as no significant differences between treatments were generally found. Nevertheless, the results may be of interest for comparison in future studies, and they have been presented as Supplementary Materials (Tables S1 and S2).

3.3. Soil Properties and Tissue Nutrient Concentration of Potted Ryegrass

Easily oxidizable C and total organic C varied significantly between treatments (Table 1). Sheep grazing treatment exhibited the highest values. Tillage treatment showed significantly lower total organic N values than the herbicide treatment and lower average easily oxidizable C values, although the latter difference was not statistically significant. The average values of total N followed the pattern of organic C but did not show significant differences between treatments. The values of pH, exchangeable bases, exchangeable acidity, and cation exchange capacity (CEC) did not vary significantly with soil management treatments. Extractable P and B were significantly lower in the tillage treatment compared to the other treatments.

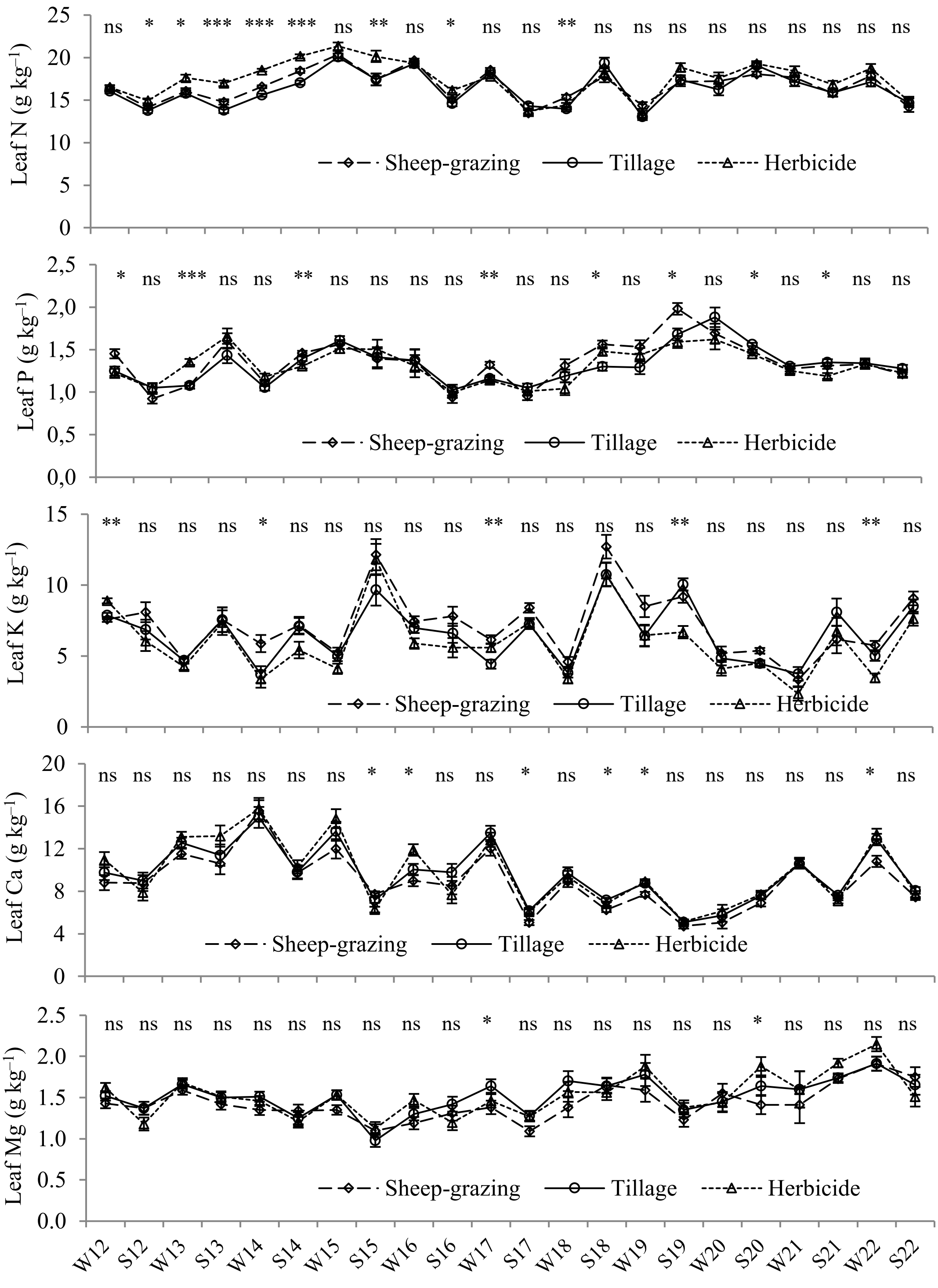

Figure 4. Leaf macronutrient concentrations (n = 10) as a function of soil management treatments from leaf samples collected during winter (W) and summer (S) between 2012 and 2022. *, **, *** significant at $p < 0.05$, 0.01, 0.001, respectively. ns, not significant. Vertical bars represent the standard error.

Ryegrass dry matter yield (DMY) varied significantly between treatments (Table 2). The soil collected from the sheep grazing treatment yielded a higher value than that from the tillage treatment, while the value for the herbicide treatment fell between the other two. The N concentration in the tissues also varied significantly between treatments, with the average value for the tillage treatment being lower than those of the other two treatments. P and B levels in the tissues tended to be lower in the tillage treatment compared to the other treatments, but the differences were not statistically significant. The other macro- and micronutrients did not show a consistent relationship with the soil management treatments.

Table 1. Effect of three soil management treatments (n = 10) on easily organic carbon (EOC), total organic carbon (TOC), total nitrogen (TN), pH, extractable P (P_2O_5) (Egnér–Riehm), exchangeable bases [calcium (Ca^{++}), magnesium (Mg^{++}), potassium (K^+) and sodium (Na^+)], exchangeable acidity (EA) and cation exchange capacity (CEC). Means followed by the same letter in the columns are not significantly different by the Tukey HSD (α = 0.05) test.

	EOC	TOC	TN		Extr. P	Ca^{++}	Mg^{++}	K^+	Na^+	EA	CEC	Extr. B
		g kg^{-1}		pH_{H2O}	mg kg^{-1}				cmol$_c$ kg^{-1}			mg kg^{-1}
Sheep grazing	19.00 a	41.26 a	2.21 a	5.68 a	179.63 a	8.64 a	1.79 a	0.40 a	0.15 a	0.13 a	11.10 a	1.65 a
Tillage	12.86 b	33.67 c	1.74 a	5.63 a	112.63 b	8.72 a	1.78 a	0.32 a	0.16 a	0.15 a	11.13 a	1.02 b
Herbicide	15.33 b	37.30 b	1.80 a	5.74 a	167.24 a	8.69 a	2.14 a	0.37 a	0.19 a	0.12 a	11.50 a	1.74 a
Prob.	0.0014	<0.0001	0.1006	0.5298	0.0005	0.9930	0.1657	0.6859	0.3703	0.1851	0.8463	0.0005

Table 2. Effect of the three soil management treatments (n = 10) on the dry matter yield (DMY) of potted ryegrass and the concentration of nutrients in the aboveground biomass. Means followed by the same letter in the columns are not significantly different by the Tukey HSD (α = 0.05) test.

	DMY	N	P	K	Ca	Mg	B	Fe	Mn	Zn	Cu
	g pot^{-1}			g kg^{-1}					mg kg^{-1}		
Sheep grazing	5.6 a	16.8 a	5.5 a	31.0 a	4.8 a	3.0 a	32.8 a	318.8 a	195.2 a	16.1 a	9.0 a
Tillage	4.5 b	15.3 b	4.7 a	32.4 a	4.4 a	2.9 a	27.9 a	325.6 a	245.0 a	18.9 a	9.0 a
Herbicide	5.0 ab	16.9 a	5.9 a	32.9 a	4.5 a	2.7 a	37.1 a	291.0 a	247.8 a	21.2 a	9.8 a
Prob.	0.0239	0.0287	0.1175	0.5215	0.1014	0.0944	0.0088	0.2212	0.1866	0.0523	0.2520

4. Discussion

4.1. Sheep Grazing Gave the Same Olive Yield as Herbicide and Tillage Treatments

The accumulated olive yield from eleven successive harvests (2012–2022) did not vary significantly among treatments. The sheep grazing treatment, which in a previous eleven-year cycle (2001–2011) had resulted in a significantly lower olive yield compared to the other treatments [8], resulted in similar values in the current study. The main difference in the management of the experimental field of the two consecutive studies was the increase in stocking rate, reducing herbaceous vegetation in the spring, a time of year when water deficit and competition for water between herbaceous vegetation and trees are expected to occur [5]. It is well known that water loss by plants depends on the size of the canopy [25–27]. Under a Mediterranean climate, spring/summer precipitation is typically lower than plant evapotranspiration, resulting in water deficit for plant growth, conditions exacerbated by climate change [28,29]. Although maintaining herbaceous vegetation in orchards, whether natural or sown, has been promoted for various benefits such as soil erosion control [6,7], increased soil C sequestration [7,16,30,31], and enhanced functional biodiversity [32,33], there is a risk of productivity loss, primarily due to competition between herbaceous vegetation and trees [12,17]. In rainfed managed orchards, this risk is even more evident due to the long drought period [8].

Thus, cover cropping may require adequate control of the vegetation, such as regular cutting with vegetation mulchers [5]. In this study, this balance was achieved through grazing, which can bring significant benefits to the farm. If vegetation is managed through grazing, with an appropriate stocking rate, costs associated with soil tillage and herbicide use are reduced. On the other hand, integrating crop–livestock farming allows for better utilization of farm resources [34,35] and increases farmer income through the sale of animals and their products [18,36]. Also, by utilizing animals in cover crop management, the transition to organic farming or regenerative agriculture practices becomes natural and facilitated [3,37].

4.2. The Alternate Bearing Habit of Olive

The fact that eleven successive olive harvests were conducted in this study, using a total of 30 trees, provided insights into the alternate bearing of olive trees that deserve commentary. Alternate bearing in fruit trees is characterized by a good harvest invariably followed by a poor one, and vice versa, known as "On" and "Off" years, respectively [38,39]. Attempts to explain this alternation have focused on hormonal effects exerted by developing seeds in the current year on the floral induction of buds that would bloom in the following year, with the involvement of gibberellins [40], auxins [38], or phenols [41] suggested. However, an equally plausible explanation considers competition for photosynthates between reproductive structures (flowers and fruits) and the development of the shoots of the current year. That is, flowers and fruits as reproductive structures are the priority sinks for photosynthates in trees [42,43]. When flowering and fruit sets are abundant, resulting in an "On" year, the high consumption of photosynthates reduces the length of the new shoots and potential sites for new flowers, along with decreased flower quality and fruit sets [44–46], directing the tree towards an "Off" year.

This study shows a clear tendency of the tree for alternate bearing, but also various disturbances to a perfect biennial cycle, where individual trees seem to deviate from the majority (Figure 3). It appears that it is in the "Off" years that the biennial cycle can be restored across all trees. The result suggests that some unfavourable environmental variables may be responsible for "Off" years, sometimes disrupting the usual biennial cycle with two consecutive unproductive years (for example, 2021 and 2022), and resetting all trees to the same phase in the biennial cycle, an "Off" year. Perhaps that is why the phenomenon becomes more pronounced under marginal growing conditions (environmental stresses or unsatisfactory quality of cropping practices), as highlighted by other authors [45,47].

4.3. The Nitrogen Nutritional Status of Tree Plants Increased with Herbicide Application

In the initial sampling dates, the herbicide treatment tended to exhibit higher N concentrations in the leaves compared to the other treatments (Figure 4). In the previous eleven years (2001–2011), the herbicide treatment was under the sheep grazing treatment, which resulted in higher soil organic matter [8]. In the 2011–2022 study, following herbicide application, as this is a systemic non-selective herbicide that kills vegetation, including its underground structures [48], an increase in organic substrate degradation is expected. Additionally, considering that herbicide application occurs in spring, when temperatures are relatively high and there is still soil moisture, these conditions are highly favourable for microbial activity and soil organic matter mineralization [49]. On the other hand, the improvement of conditions for mineralization occurs in the absence of live herbaceous vegetation, which was killed by herbicide application, favouring nutrient uptake by the olive tree as it no longer faces competition from herbaceous species. However, the process of mineralization and biological immobilization tends towards balance over time as the cropping system stabilizes [50,51]. Thus, after the initial years, a new equilibrium will have been established with herbicide use, where inputs and outputs of organic substrate in the soil balance out, leading to no significant differences in N concentration in the leaves between treatments.

Although significant differences were recorded in the N nutritional status of the trees between treatments, no significant effects were observed on olive yield. This may have occurred because N concentrations in the tissues remained above the lower limit of the sufficiency range [52] in all treatments. Nonetheless, it was in the initial years that the average olive yield values were highest in the herbicide treatment, particularly in 2014.

The concentrations of other macro- and micronutrients in the leaves did not consistently vary with the treatments. However, some nutrients showed a stable variation with the sampling date, with large differences between winter and summer sampling values. In general, the main mechanisms explaining these differences are the role of nutrients in the plant and source-sink relationships. For example, K does not integrate organic structures but appears in high concentrations in fruits [53]. Thus, its concentration in leaves was lower in winter, close to harvest, as part of the nutrient was remobilized to the growing fruits [52,54,55]. For example, Ca is mostly associated with cell walls [46]. In summer, the sampled leaves in the new shoots are young, while in winter, during the resting period, they are older, containing a higher amount of Ca. The trends reported here are consistent with several other recent studies on these nutrients [55–57].

4.4. The Pool of Soil Organic Carbon and Some Nutrients Varied with the Treatments

Considering the combined effect of treatments on the pool of soil organic C (EOC and TOC) and total N, it becomes evident that values were lower in the tillage treatment and higher in the sheep grazing treatment, although in the case of total N, no significant differences were observed between treatments. The sheep grazing treatment allows for greater herbaceous vegetation development, ensuring a higher input of organic C into the soil. On the other hand, soil tillage stimulates the mineralization of organic matter by promoting soil aeration, as most of the microorganisms that degrade organic matter are aerobic [49]. Thus, comparing sheep grazing with tillage results in two combined effects: in the former, there is a greater deposition of organic substrate in the soil, while in the latter, there is greater biological degradation, resulting in significant differences between the two treatments. These are the main effects that justify the results observed in this study and are consistent with most of the literature published so far, which reports increases in soil organic matter in soil management systems with cover crops compared to tillage systems [7,8,30,31].

The soil tillage treatment also appeared to be associated with lower levels of extractable P and B in the soil. Soil management treatments themselves do not introduce P or B into the soil. However, both nutrients are associated with important structural functions in the plant [53,58]. Thus, as nutrients are taken up, they are incorporated into plant tissues, later appearing in the soil organic matter. In practice, in soil management systems that allow for greater herbaceous vegetation development, more P and B are taken up by these plants, leading to an increase in nutrients in the soil organic substrate. This additional pool of nutrients becomes available to the trees as the soil organic matter mineralizes [49]. Although the effect had not been clearly observed in the concentration of nutrients in olive leaves, significant differences in the extractable amount of these nutrients in the soil were already observed.

4.5. Soil Tillage Reduced Potentially Available Soil Nitrogen

The growth of ryegrass in a pot experiment, using soil sampled from the last year of the field trial, served as a biological indicator of nutrient availability for plants, a methodology previously successful in other studies [8,16]. The soil, subjected to cycles of wetting and drying associated with ryegrass irrigation, creates conditions of aeration and moisture not found in the field, stimulating organic substrate mineralization by enhancing microbial activity [49]. The results indicated lower levels of DMY in the tillage treatment (Table 1). The primary factor limiting growth and resulting in a lower DMY of ryegrass in the tillage treatment was N supply, as the nutrient concentration in the tissues was significantly lower compared to the other two treatments.

Given that N occurs in relatively high concentrations in soil organic matter, typically containing about 5% N [49], it is the nutrient that is usually released to plants in greater amounts during soil organic matter mineralization [59–61]. For other nutrients such as P and B, lower average values were also recorded in the tillage treatment compared to the others, but without significant differences. This result is somewhat consistent with the values of extractable P and B directly from soil samples and is also justified by the association of these nutrients with soil organic matter [49].

5. Conclusions

The comparison of three soil management systems in a rainfed olive orchard, namely, conventional tillage with a cultivator, non-selective herbicide (glyphosate) application over the entire soil surface in early spring, and ground management by grazing with a stocking rate that substantially reduced herbaceous vegetation in spring, showed no significant differences in olive yield among treatments. After eleven years, soil tillage resulted in lower soil organic C content and reduced bioavailability of some important nutrients, questioning the sustainability of this soil management system. On the other hand, ground management through grazing, besides ensuring an olive yield equivalent to other treatments, allows for increased income for the farmer through the sale of animal products and facilitates the adoption of organic farming systems, including regenerative agriculture practices, increasingly demanded by contemporary societies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14060897/s1, Figure S1. Leaf micronutrient concentrations (n = 10) as a function of soil management treatments from leaf samples collected during winter (W) and summer (S) between 2012 and 2022. *, **, *** significant at $p < 0.05$, 0.01, 0.001, respectively. ns, not significant. Vertical bars represent the standard error; Table S1. Fruit dry weight and pulp/pit ratio (n = 10, 30 fruits per sample) in relation to soil management treatments over two years of sampling (2019 and 2021); Table S2. Nutrient concentration in pulp and pit (n = 10) as a function of soil management treatments in two years of sampling (2019 and 2021).

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