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Hedgerow Olive Orchards versus Traditional Olive Orchards: Impact on Selected Soil Chemical Properties

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Abstract: Olive orchards cover over 10 million hectares worldwide, with production techniques undergoing significant changes in the past three decades. The traditional rainfed approach, involving minimal inputs, has given way to irrigated super-intensive systems with higher planting density, increased productivity, a greater use of fertilizers and phytopharmaceuticals, and total mechanization. Its impact on soil chemical properties remains a topic of great debate, and no definitive consensus has been reached. Our main objective was to examine the different effects of traditional olive orchards and super-intensive orchards on soil chemistry over a decade. We collected and analyzed 1500 soil samples from an irrigation perimeter in southern Portugal in 2003 and 2013. Our findings indicate that, compared to traditional olive orchards, super-intensive ones show, in a decade, a significant decrease in soil organic matter (less 22.8%—$p < 0.001$), namely due to the increase in mineralization caused by an increase in soil moisture content as a result of irrigation practice, and an increase in sodization (more 33.8% of Ext Na—$p < 0.001$) highlighting the importance of monitoring this factor for soil fertility. In comparison to other irrigated crops in the region, super-intensive olive orchards promote a significant soil acidification (from 7.12 to 6.58), whereas the pH values of the other crops increase significantly (3.3%, 13.5%, and 3.0% more in corn, tomato, and cereals, respectively). Mainly because of the decrease in organic matter levels with soil acidification and soil sodization, we can underline that hedgerow olive orchards can affect soil characteristics negatively when compared with traditional ones, and it is necessary to adopt urgent measures to counter this fact, namely sustainable agriculture practices.

Keywords: hedged olive grove; mediterranean region; soil chemical characteristics; traditional olive grove

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1. Introduction

Olive groves have been a prominent crop in the Mediterranean region for over 6500 years, holding significant sociocultural and economic importance [1,2]. With a global area of approximately 10 million hectares, over 90% of olive groves are concentrated in the Mediterranean Basin [3]. The expected olive oil production for 2021/2022 was 3116×10^3 Mg, with Spain (38%), Italy (11%), Greece (11%), and Portugal (9%) being the largest producers [3]. Notably, worldwide olive oil production has experienced significant growth in the past five years, with Portugal and Italy recording increases of 78% and 15%, respectively, while Spain and Greece witnessed declines of 6% and 18%, respectively [3].

Traditionally, in the Mediterranean, olive groves were rainfed and had low tree densities (50–100 trees per hectare) in marginal agricultural areas [4–6]. These groves thrived in conditions less suitable for other crops, such as water scarcity [7]. The productivity of rainfed olive groves was relatively low, yielding 500 to 600 kg of olives per hectare, and relied heavily on manual labor [8]. However, since the 1980s, olive grove cultivation has undergone significant changes to enhance economic performance and address labor shortages. This shift involved adopting irrigation, mechanization (all the cultural operations, from plantation to harvest, are mechanized), higher planting densities (1800 to 2200 trees per hectare), and the use of fertilizers and phytopharmaceuticals [9–12]. These changes led to substantially higher and more stable yields, reaching 12,000 to 14,000 kg of olives per hectare.

Nevertheless, this intensification of olive grove production has generated considerable controversy, with critics highlighting various concerns. Criticism focused on the decrease in biodiversity due to the transformation of traditional rainfed groves into super-intensive ones [13–15], and the relatively high water consumption of new production systems, approximately 3000 m^3 per hectare, raising sustainability concerns considering increasing water scarcity due to climate change [10,16].

The impact of these new production systems on soil properties is also a subject of debate [9]. Potential impacts include increased soil erosion risk in sloped areas, compaction from machinery traffic, decreased soil organic matter content due to irrigation-induced mineralization, changes in soil pH through base cation leaching and acidifying fertilizers, increased salinity from irrigation water and fertilizers, and surface and groundwater contamination from the leaching of fertilizers and phytopharmaceuticals [17–20]. However, there are contrasting opinions regarding the impacts of super-intensive olive groves. In the case of rainfed areas converted to irrigated groves, the changes in soil physical, chemical, and biological characteristics are notable, but are primarily associated with introducing irrigation rather than a specific crop [21–23]. When super-intensive olive groves replace other crops under irrigation, some argue that the negative effects may be less pronounced compared to alternative crops. Super-intensive olive groves generally use less water and fewer fertilizers than other irrigated crops, resulting in potentially lower impacts on soil properties such as pH, salinity, and organic matter content [20,24–26]

Given the ongoing expansion of super-intensive olive groves in the southern Iberian Peninsula and the lack of consensus among researchers regarding their impact on soil properties, our study aims to investigate the changes in the chemical composition of a Fluvisol soil (most representative of the region) under two different crop systems (super-intensive olive groves and rainfed olive orchards) over a decade. We will also compare the impacts of hedgerow olive orchards with other irrigated crops, such as maize, tomato, and cereals, on selected soil chemical properties.

By conducting this study, we aim to contribute to understanding the effects of super-intensive olive groves on soil chemistry and provide valuable insights for sustainable olive grove management practices in the context of evolving agricultural systems.

2. Materials and Methods

2.1. Study Area and Sampling

The region in which this study was developed is located in the Center–South of the Iberian Peninsula, in a Portuguese region called Alentejo, covering part of the Municipalities of Campo Maior and Elvas (Figure 1), precisely in the Caia Irrigation Perimeter, covering 7240 ha and the surrounding agricultural areas for a total of 15,030 ha. The region's climate is characterized by hot, dry summers and mild winters with high rainfall (average annual rainfall of 457.4 mm and a mean annual evapotranspiration of roughly 813.2 mm—data on the 1991–2020 climate normal). The month with the highest temperature is August, with an average monthly maximum temperature of 34.9 °C, and the coldest month is

January, with an average monthly minimum temperature of 4.5 °C. According to Koppen, the region's climate is classified as Csa, while according to Thornthwait, it is determined as DB2db4, i.e., mesothermal semi-arid, with little or no excess water in the winter and very low thermal efficiency in the summer.

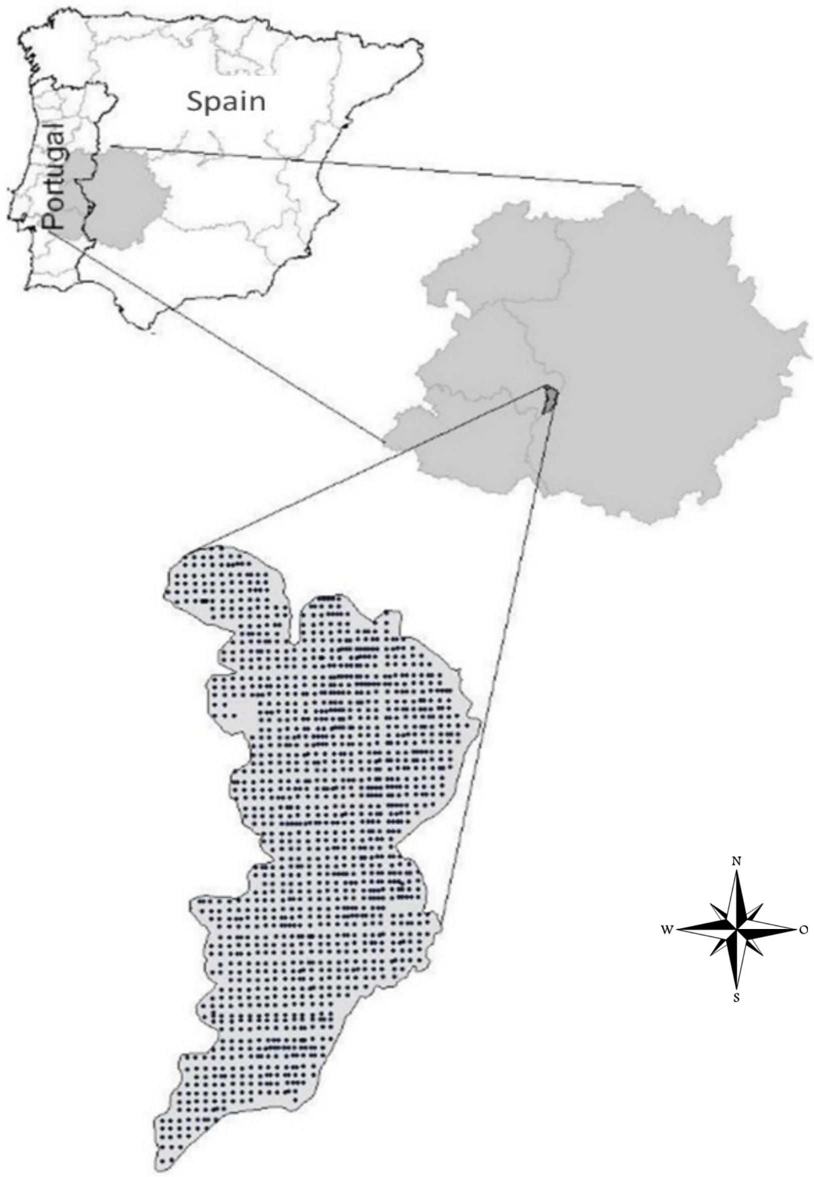

Figure 1. Location map of the study area and sampling points.

The region is geologically heterogeneous, consisting of Quaternary conglomerates, Paleogene sandstones, Neoproterozoic phyllites, Devonian gabbro, Carboniferous granites, and Cambrian limestones (Figure 2). The soils of the study area, classified according to the World Reference Base for Soil Resources [27], are mainly divided into 4 groups—Fluvisols, Luvisols, Calcisols, and Cambisols—and in this work, due to their greater representativeness, which allows us to carry out a more consolidated statistical analysis, we will only consider Fluvisols.

The most representative crops in the study area in 2012 were olive groves (*Olea europaea* L.) at 35%, corn (*Zea mays* L.) at 20%, tomato/vegetable crops (*Lycopersicon esculentum* Mill.) at 15%, and garlic (*Allium sativum* L.) at 15% (Figure 3). The olive groves considered in this study are more than 10 years old and are the same as those were previously analyzed in 2002 and 2012, according to their location.

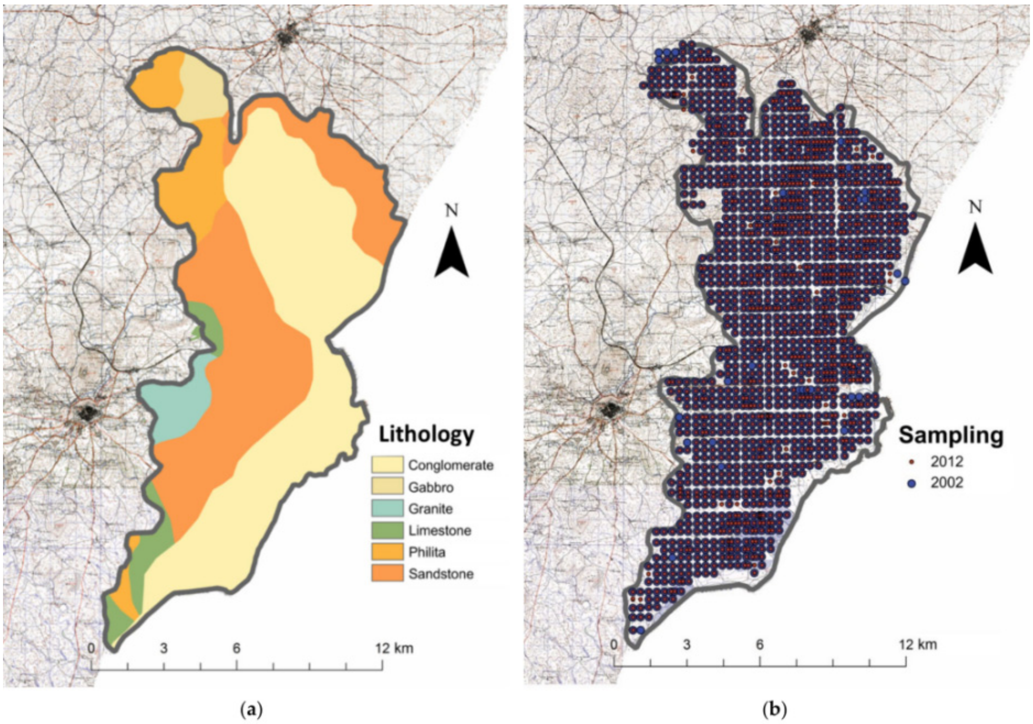

Figure 2. Study area lithology (**a**) and sampling points (**b**). Source: Telo da Gama et al., 2021 [28].

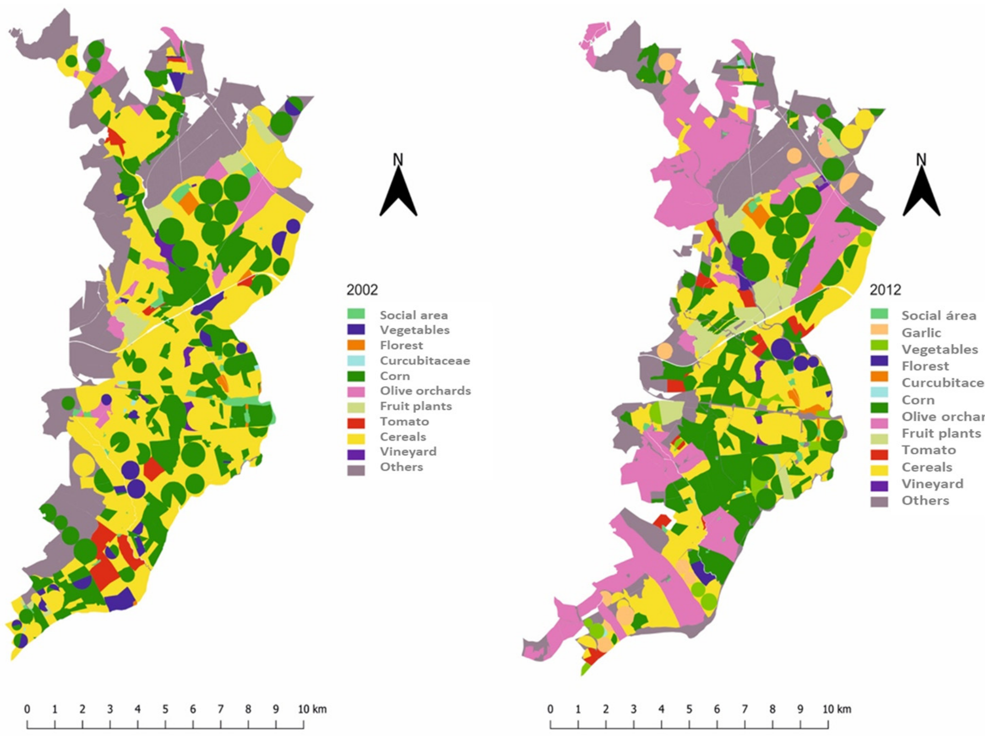

Figure 3. Crop distribution in the study area in 2002 and 2012.

Regarding tomatoes, considering that they should not be planted consecutively in the same area—for phytosanitary reasons—though it is the most relevant crop in the rotation, it is generally interspersed with other horticultural crops. The vegetable crops in bi-annual rotation with tomatoes are mainly broccoli (*Brassica oleracea*), garlic (*Allium sativum*), and pepper (*Capsicum annum*). A short characterization of the amounts of water and fertilizers used on the main crops of the region, as well as their average yield, can be seen in Table 1.

Table 1. Characterization of agronomic techniques for the crops analyzed.

Crop	Water Consumption $m^3\ ha^{-1}$	N Fertilizer $kg\ ha^{-1}$	P Fertilizer $kg\ ha^{-1}$	K Fertilizer $kg\ ha^{-1}$	Average Yield $Mg\ ha^{-1}$	Irrigation System
Olive orchard—traditional	0	50	50	30	0.8	-
Olive orchard—hedgerow	3000	160	160	120	14	Drip
Corn	8000	220	180	160	12	Sprinkler
Tomatoes/vegetables	6500	200	180	200	85	Drip
Cereals	2500	120	120	80	4	Sprinkler

The irrigation water used in the perimeter and adjacent areas (Table 2) is of good quality, classified according to the FAO classification as C1S1 and in the summertime as C1S2, which means water of low salinity and sodicity. The quality remained approximately unchanged over the decade under review.

Table 2. Average, minimum, and maximum values for several water quality parameters measured monthly over the decade under analysis.

Parameter	Mean Value	Min–Max
Temperature (°C)	19.7	15.6–24.0
pH	7.9	7.3–8.5
EC (dS m^{-1})	0.20	0.19–0.21
Ca (mg L^{-1})	18.7	16.3–23.4
Mg (mg L^{-1})	6.7	5.7–7.2
Na (mg L^{-1})	11.2	8.6–13.9
NO_3^- (mg L^{-1})		Vest–2.2
Cl (mg L^{-1})	18.4	17.7–20.2
HCO_3 (mg L^{-1})	63.5	58.6–70.7
P (mg L^{-1})	5.0	4.5–5.4
K (mg L^{-1})	2.7	2.2–3.1
SAR	0.17	0.14–0.22

The sampling depth and the analytical methods were the same in 2002 and 2012.

A total of 631 and 526 topsoil samples were analyzed in 2002 and 2012 (each one of these samples came from the combination of 10 subsamples randomly collected in the area they represent), respectively, in the Fluvisols [27] of the study area. Ten soil samples were collected using a stainless-steel drill from the topsoil layer (0–20 cm) per sampling unit. The sampling sites were chosen to cover some of the existing variability in the sampling area. The soil samples were carefully mixed into one composite sample and sent to the laboratory after proper a inventory and labeling. The samples were then air-dried in the laboratory and sieved through a 2 mm square mesh stainless-steel sieve. After this phase, the corresponding analysis was performed. A brief description of the dominant topsoil properties of this reference soil group (RSG) for 2012 was presented by Telo da Gama et al. (2021) [28]. For the 2002 edaphic description, please refer to Telo da Gama et al. (2019) [23].

2.2. Soil Data and Analysis

2.2.1. Analytical Methods

The pH (water) and EC were determined in a 1:5 (*w*/*v*) solution. The pH was measured by potentiometry (pH/ion MTROHM 692) and the EC with a conductivity meter (WPA CMD 8.500) [29]. Soil organic matter was obtained using the method of wet oxidation with dichromate potassium, with measurements of excess dichromate by titration with ferrous sulfate [30].

The plant-available Ca and Mg values were extracted with a buffered ammonium acetate solution at pH 7.0, with the addition of a 10% of lanthanum chloride solution, and their determination was carried out by atomic absorption spectrophotometry with flame atomization in a Perkin Elmer Analyzer A300 [31]. Data for plant-available K, P, and Na were extracted with a solution of ammonium lactate and acetic acid buffered at pH 3.65–3.75 [32], and their determination was obtained by atomic absorption spectrophotometry with flame atomization on a Perkin Elmer Analyzer A300 apparatus.

The extractable metals were determined using the method described by the USDA (1996) [31], extraction with DTPA + $CaCl_2$ + triethanolamine and quantification by flame atomization atomic absorption spectrophotometry with a Perkin apparatus Elmer Analyzer A300.

2.2.2. Statistical Analysis

To determine whether the sample data from 2002 and 2012 were normally distributed, statistical analyses were carried out using the software package SPSS (v.25). These analyses included tests of normality (Shapiro–Wilk) [33,34]; examinations of kurtosis, skewness, and standard errors [35–37]; and a visual inspection of the histograms, normal Q-Q plots, and box plots. In this subset, tests for the homogeneity of variances (Levene's) [38,39] were also conducted to determine the homoscedasticity/heteroscedasticity of the data. With more than 30 samples per subgroup and non-normally distributed data with a homogeneity of variances, we performed independent sample t-tests on all normally distributed data with a homogeneity of variances from 2002 and 2012, and we applied the central limit theorem. For the mean rank (MR), we performed a direct analysis of data using the Mann–Whitney U Test (U) or the Kruskal–Wallis H test (H) on data with non-normal distribution and no homogeneity of variances. If $p < 0.05$, all null hypotheses were rejected.

3. Results

3.1. Traditional Olive Orchards versus Hedgerow Olive Orchards

3.1.1. pH

Although not statistically significant, there was a slight decrease in soil pH in both crop systems under analysis (Figure 4). However, while, in rainfed olive groves, this decrease was only 0.03, in the case of irrigated olive groves, this decrease was 0.54.

3.1.2. Soil Organic Matter (SOM)

Regarding soil organic matter, there is a significant difference between traditional rainfed olive orchards and hedgerow-irrigated olive orchards. While, in the first case, the SOM content remains almost constant during the period under analysis, even registering a slight, non-significant increase, in the second case, the SOM content decreases significantly (a decrease of 22.8%). This result is important, given the importance that this soil component, normally with very low levels throughout the Mediterranean Basin, has in terms of soil physical, chemical, and biological properties [40]. This result is also important when we analyze the different influences of these two agro-systems on carbon sequestration and, consequently, on the climate crisis [41].

3.1.3. Electrical Conductivity (EC)

Concerning electrical conductivity, we obtained results contrary to what would be expected, and to the ones reported by, for example, Ramos et al. (2019) [19]. Thus, while, in hedgerow olive groves, the values of this parameter did not change significantly during the decade under analysis, in the case of rainfed olive groves, this value rose significantly.

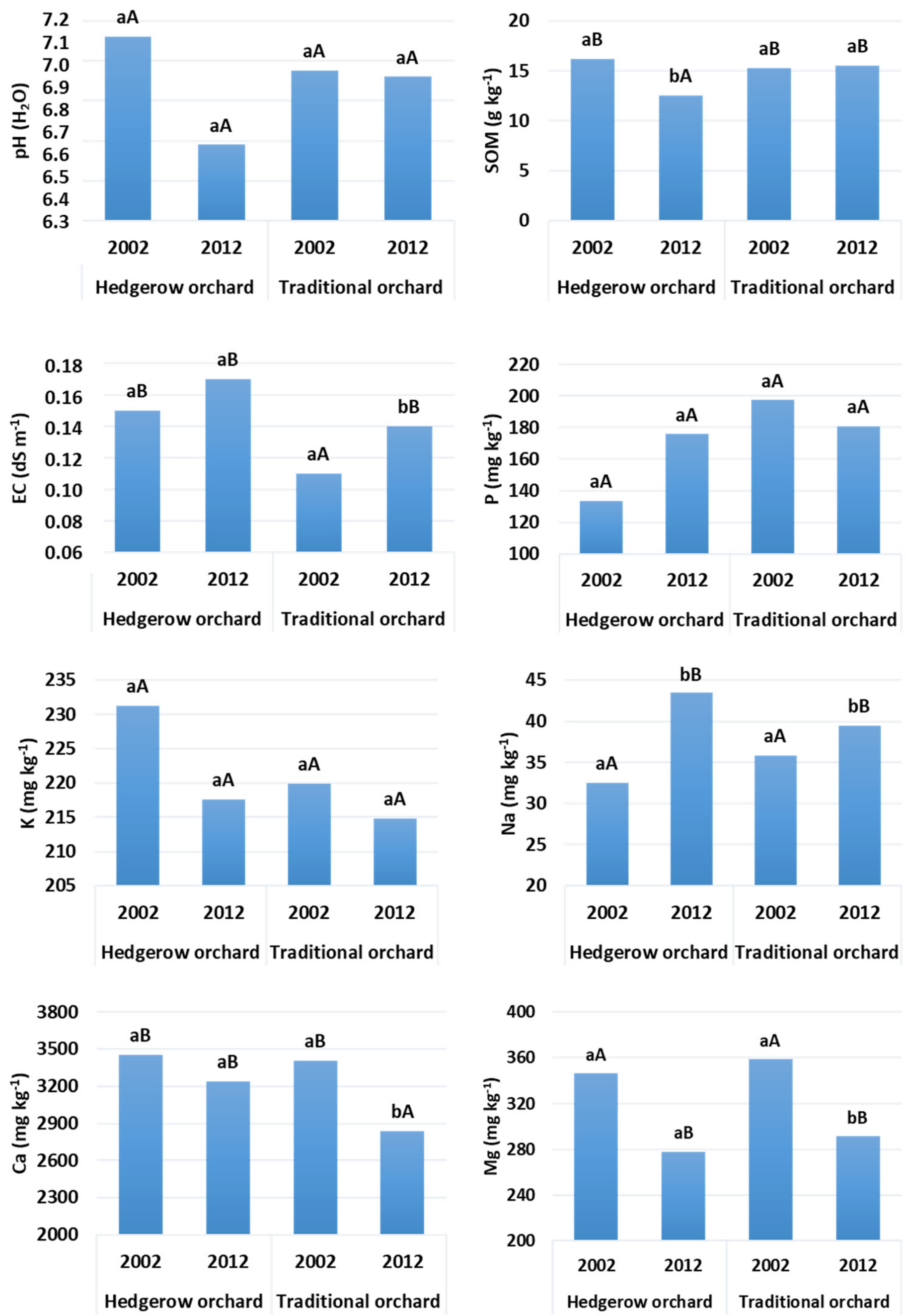

Figure 4. Differences in some selected soil chemical characteristics (pH, SOM, EC, P, K, Na, Ca, and Mg) between different olive production systems (capital letter) and in each production system between different dates (lowercase letter).

3.1.4. Extractable P, K, Ca, Mg, and Na

In the case of extractable phosphorus and potassium, there were no significant differences, either over time or amongst crop systems. Regarding extractable Ca and Mg in the soil, there was a highly significant decrease in the levels of these elements in the traditional rainfed olive groves. In the super-intensive irrigated olive groves, although there was a slight decrease, this result is not statistically significant.

Regarding extractable sodium, directly related to the sodium content in the exchange complex [23], an important element that can have a harmful effect on the soil structure when and if it exists in the soil exchange complex in excessive amounts (more than 10%), we found a significant increase in both production systems. In the case of super-intensive olive groves, this increase is highly significant ($p < 0.001$) and corresponds to an increase of 33.8%. In the case of traditional rainfed olive groves, this increase is also significant ($p < 0.05$) and corresponds to an increase of 10.3%. It should also be noted that, in 2002, the rainfed olive groves had a slightly higher soil-extractable sodium content than the irrigated olive groves (3% lower). However, this trend was reversed in just a decade. Nowadays, the super-intensive irrigated olive grove presents a soil-extractable sodium content 10% higher than the non-irrigated ones.

3.1.5. Extractable Cd, Cu, Fe, Zn, Pb, Ni, and Mn

Regarding Cd, Cu, Fe, Zn, Ni, Pb, and Mn, as we can see in Table 3, in the case of the super-intensive irrigated olive groves, the contents of all of these elements grew over the decade considered, with this growth having statistical significance in the cases of Cu, Fe, and Ni. In the case of the traditional rainfed olive groves, the levels of Cd and Ni decreased, with statistical significance, and the levels of Zn and Mn increased significantly.

Table 3. Evolution over a decade of extractable Cd, Cu, Fe, Zn, Ni, and Pb in a hedgerow olive orchards versus traditional olive orchards.

Parameter	Hedgerow Olive Orchard		Sig	Traditional Olive Orchard		Sig
	2002	2012		2002	2012	
Cd (mg kg^{-1})	0.15	0.37	NS	0.17	0.13	***
Cu (mg kg^{-1})	2.6	4.1	*	1.4	4.6	NS
Fe (mg kg^{-1})	38.6	52.1	*	60.0	67.2	NS
Zn (mg kg^{-1})	0.74	3.93	NS	0.71	1.40	**
Pb (mg kg^{-1})	2.9	3.6	NS	3.3	3.7	NS
Ni (mg kg^{-1})	2.9	4.8	***	2.0	1.8	***
Mn (mg kg^{-1})	52.0	57.9	NS	48.0	64.6	***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and NS: not significant.

3.2. Hedgerow Olive Orchard versus Other Irrigated Crops (Corn, Tomato, Cereals, Others)

When we analyze the evolution, over a decade, in the soil chemical composition as a function of the crop installed in the irrigated area (Table 4), several results are worth mentioning.

Table 4. Differences in selected soil chemical characteristics between crops over a decade.

Parameter	CROP											
	Maize		Tomato/Vegetable		Cereals		Olive		Others		Sig.	
	2002	2012	2002	2012	2002	2012	2002	2012	2002	2012	***	***
pH	6.52aA	6.74aB	6.59aA	7.48bB	6.97bA	7.18bB	7.12cA	6.58abA	6.67abA	7.12bA	***	***
EC (dS m^{-1})	0.19baA	0.24cbB	0.19bA	0.20bA	0.11aA	0.15aB	0.15aA	0.17abA	0.12aA	0.16abB	***	***
SOM (g kg^{-1})	11.9bA	12.0bA	10.4aA	10.4aA	14.6cA	15.8cA	16.2dB	12.5bA	14.2cB	11.8bA	*	***
P(mg kg^{-1})	164abA	205abB	165abA	225bB	181abA	222bA	133.6aA	175.8aA	232bA	200abA	**	***
K(mg kg^{-1})	227.0bcA	260.0cB	197.3abA	238.0bcA	220.3bcA	194.5aA	231.3cB	217.6abA	179.0aA	238.5bcB	***	***
Ca(mg kg^{-1})	2166aA	2281aA	2439aA	4119cB	3561bA	2015aA	3455bA	3236bA	2454aA	2622aA	***	NS
Mg(mg kg^{-1})	263aA	285aA	288abA	295aA	354cA	294aA	346cB	278aA	337bcB	322aA	***	***
Na(mg kg^{-1})	46.4bA	53.5cdB	48.9bA	50.6cdA	37.5abA	60.9cB	32.5aA	43.5bB	41.3bA	49.4bcA	***	***
Year	*F*-values	Sig.	*F*-values	Sig.	*F*-values	Sig.	*F*-values	Sig.	*F*-values	Sig.		
pH	7.80	**	34.0	***	15.9	***	0.582	NS	0.004	NS		
EC	8.85	**	0.079	NS	29.4	***	2.52	NS	4.78	*		
SOM	0.002	NS	0.019	NS	0.641	NS	59.6	***	6.13	*		
P	14.2	***	4.76	*	3.36	NS	2.09	NS	1.26	NS		
K	10.4	**	3.43	NS	2.50	NS	7.78	**	7.99	**		
Ca	0.931	NS	16.1	***	0.050	NS	0.901	NS	3.37	NS		
Mg	2.77	NS	0.098	NS	3.41	NS	18.2	***	9.38	**		
Na	9.33	**	0.196	NS	22.7	***	32.4	***	0.001	NS		

F-values indicate the significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and NS: not significant. Different letters indicate differences ($p < 0.05$) between crops in the same year (lowercase letters) and between years within the same crop (uppercase letters).

3.2.1. pH

Regarding the soil pH, we found that most crops grown in the Caia Irrigation Perimeter region led to soil alkalinization, which is significant in the case of corn, tomatoes, and cereals. This alkalization is particularly evident in the case of tomatoes, with increases of 1.13 units.

The exception to this scenario occurs in olive orchards, where there is a small decrease, not statistically significant, in pH.

3.2.2. Electrical Conductivity (EC)

Although not reaching potentially risky values, the electrical conductivity of the soil increased over the decade under analysis in all crops, and these differences were significant in the case of corn, cereal crops, and "other crops".

3.2.3. Soil Organic Matter (SOM)

Regarding the soil organic matter, we can see that, in the case of corn, tomatoes, and autumn/winter cereal crops, there were no significant changes over the decade considered. In the irrigated olive orchards, the result is different, with a significant decrease in soil organic matter content over the decade under analysis.

3.2.4. Extractable P, K, Ca, Mg, and Na

In the case of extractable phosphorus and potassium, the results obtained are closely dependent on the application of fertilizers, given that these parameters have an anthropogenic influence much higher than those observed for the parameters treated above, with a strong inter-annual and intra-annual variation. However, we can refer to the trend of the growth of soil phosphorus levels in the considered crops over the decade under analysis, which is significant in the case of corn and tomato.

For extractable potassium, the dependence on fertilizer application is like the one we described for phosphorus. In the results, we can notice a significant increase in the potassium content of soils occupied with corn (the crop that receives the greatest amounts of fertilizers) and a significant decrease in the levels of potassium in soils occupied with olive orchards.

Regarding extractable Ca, there were no general trends in their content variation. So, in the case of corn and olive orchards, no significant variation occurred. Nevertheless, in the case of tomatoes, we can verify a significant increase in the extractable Ca concentration, which could be explained by the specific needs for this nutrient of this crop.

Regarding the soil-extractable Mg content of corn and tomatoes, we could not verify any significant variation over the decade under analysis; in the case of olive orchards, we can notice a significant decrease in the extractable Mg content.

Regarding extractable sodium, directly related, as we previously mentioned, to exchangeable sodium, we can notice that it rises significantly in all crops analyzed during the considered decade. It is important to notice that there was a greater increase in sodium levels in the olive and cereal crops and, although equally significant, a smaller increase in the tomato and corn crops.

4. Discussion

4.1. Traditional Olive Orchard versus Hedgerow Olive Orchards

4.1.1. pH

The differences registered in pH values between the analyzed systems, although not significant, can be a consequence of the applied nitrogen fertilizer, practically not used in rainfed olive groves yet used in high amounts in irrigated olive groves (150 to 170 kg N ha^{-1} $year^{-1}$). When nitrogen is applied in the ammoniacal form, which often happens to reduce the losses of this nutrient by leaching, the natural process of nitrification leads to the acidification of the soils [23]. Other explanations, such as the leaching of basic cations, do not apply here, since irrigation is strictly controlled, and there is no possibility of a significant increase in the leaching process due to the irrigation practice.

Also, organic matter mineralization can have some influence on this result, because, as we have seen before, the SOM mineralization is bigger in the irrigated olive groves and therefore can contribute to soil acidification.

Soil acidification is a very important edaphic issue that leads to cation leaching, instability in the soil structure, increased heavy-metal toxicity, and modified soil nutrient availability, and consequently affects the soil's chemical, physical, and biological properties and plant production [42]. To counteract this phenomenon, farmers in the region sometimes apply limestone to soils occupied by hedgerows olive groves, given the olive grove's known preference for slightly alkaline soils.

4.1.2. Soil Organic Matter (SOM)

The organic matter content in the soil depends, among other aspects, on two antagonist mechanisms: mineralization and the production and deposition of organic matter [21]. A problem arises because the factors that lead to an increase in organic matter mineralization, among which are soil tillage and the introduction of irrigation, are the same factors that lead to an increase in the production and deposition of organic matter. Besides this, it becomes extremely difficult to completely separate each of the factors that lead to an increase or decrease in SOM, given that, for example, the introduction of irrigation is almost always associated with an intensification in soil tillage and/or the use of fertilizers and the introduction of new crops or varieties, and it is not possible to know exactly which of these changes is the most influential one in the variation of soil organic matter content [40].

It is important to note that, when we go from traditional rainfed olive groves to irrigated olive groves, many factors affecting soil organic matter content must be considered besides the introduction of irrigation and fertilizers, such as the type of tillage carried out, the existence or lack of cover crops between the rows, and the incorporation or absence of pruning residues [43]. In fact, Sobreiro et al. (2023) [44] said that, with the combined utilization of cover crops, non-tillage, and pruning residue recycling, it is possible to reduce soil erosion and nutrient leaching and improve the soil organic carbon by 2 to 3 Mg C ha^{-1} $year^{-1}$.

Costa et al. (2008) [45] empathize the close relation between soil organic matter and nitrogen content and cultural practices, highlighting that whenever soil movement occurs, we will promote the mineralization of SOM, something to take into account in the south of the Iberian Peninsula. González-Rosado et al., 2020 [46], also highlight the importance of the mobilization system in the organic matter content of Mediterranean soils, concluding that non-mobilization systems are those that allow for the maintenance of organic matter contents in these soils, unlike systems of conventional mobilization which, by promoting greater soil aeration and therefore SOM mineralization, leads to a decrease in SOM levels.

What we have in use today are SOM preservation techniques, but this was not always the case, and organic matter loss by mineralization was a recurring factor. Nevertheless, according to Yu et al. (2019) [47], soil moisture has the highest correlation with soil organic matter mineralization, explaining between 54.8 and 62.2% of this process in Mediterranean regions. If we consider temperature and soil moisture, according to Rey et al. (2002) [48], the two factors can explain about 91% of the soil mineralization processes in semi-arid conditions.

While the introduction of irrigation seems to lead to an increase in the SOM content worldwide, with an increment between 11 and 35% as reported by Trost et al. (2013) [49], at a more local level, the results are very distinct and vary according to the situation. McGill et al. (2018) [50] report increases in soil organic matter content, of 1% per year, for 12 years at least, in an irrigated maize crop, when compared with rainfed plots of the same crop.

According to Francaviglia et al. (2017) [51], the introduction of irrigation leads to greater water availability in the soil, especially in the hottest period of the year, which promotes biological activity and, consequently, organic matter mineralization. This author, working on a Cambisol, noticed that the introduction of irrigation water into a previously rainfed agricultural system leads to a much higher organic matter oxidation, which does not happen in rainfed systems due to the lack of humidity during the summer, when the organic matter mineralization process practically ceases. Also, Rotenberg et al. (2005) [52] refer to reductions of 18% in SOM content when moving from rainfed to irrigated wheat production. Evrendilek et al. (2004) [53], working on a Tipic Haploxeroll, report that cultural intensification caused by irrigation led to a 50% decrease in soil organic matter content, which led to increases in bulk density and erosion risk of, respectively, 10.5% and 46.2%.

At the same time, Cavvadias et al. (2018) [12], in their work on 45 olive groves in Greece over a 5-year period, found that the introduction of irrigation did not lead to significant changes in the soil organic matter content. The authors attribute this result to the fact that the region is very rainy, which meant that irrigation did not substantially affect soil moisture conditions. These results demonstrate that the influence of irrigation in olive groves on the soil organic matter content depends greatly on the rainfall conditions in which the olive grove is exploited. Nevertheless, is clear from the bibliography consulted that the introduction of irrigation in regions with a greater water deficit, where olive groves typically appear, leads to significant decreases in the levels of this important soil component.

It is also important to notice that the new intensive irrigated olive orchards are fertilized, unlike traditional rainfed olive orchards where fertilization was very low or non-existent. The effect of fertilization depends, however, on factors such as the fertilizer used, the amounts applied, and the pH of the soil. Works such as those by Álvaro-Fuentes et al. (2012) [54], unlike our work, arrive at results that the application of nitrogen in the amounts of 60 and 120 kg N ha^{-1} leads to increases in the SOM content, both in the no-tillage system and in conventional tillage system, due to the increase in biomass production, an important aspect that we already mentioned before. An opposite result arrived from Deng et al. (2017) [55] which claims that the addition of fertilizers, namely nitrogen fertilizers, accelerates the decomposition of organic matter by soil microorganisms, and therefore, the SOM content tends to decrease. As we mentioned before, the balance between the production and mineralization of organic matter is something that depends on many factors and it is likely that, in soils with a high lack of nutrients, the increases in plant matter production promoted by fertilization will be more evident and overcome the greater mineralization that may occur, while in soil with greater amounts of nutrients, this effect is no longer noticeable. This is an aspect that farmers should take into consideration when managing their olive groves.

4.1.3. Electrical Conductivity (EC)

The introduction in soil of ions by irrigation water and fertilization would lead to the assumption that EC values would be bigger in olive groves managed in hedgerows, where these inputs are used to a greater extent, compared with the traditional ones [44]. In fact, irrigation, even with good-quality water, introduces appreciable quantities of salts into the soil. In our case, for an average irrigation water application of 3000 m^3 ha^{-1} $year^{-1}$, and considering the average composition of the irrigation water used (Table 2), we introduce into the soil, for example, approximately 55.2 kg Cl ha^{-1} $year^{-1}$ of chloride annually.

Nevertheless, our results also showed that traditional olive groves, without irrigation or fertilization in most cases, although with lower values, had a more pronounced increase in the EC in this period. This result may be due to a greater evaporation in the latter system, bringing to the more superficial soil layers ions that were not washed away during the winter period [56] because of the lack of rain, enhanced by climate change [2,57], which led to a precipitation decrease in this region of around 20% in a decade. This result also contributes to the fact that the irrigation water used in a very controlled quantity, as previously mentioned, was of good quality, and therefore, the potential EC increase in irrigated areas was not so evident.

In addition to this, olive groves grown under hedges, with greater growth and production potential, inevitably have a greater uptake of ions when compared to traditional rainfed olive groves [44], and therefore, the ion concentration in the top layer of the soil in the first system can be lower. Nevertheless, the registered values, in both cases, are very low and without any possibility of negatively affecting the development of this crop.

4.1.4. Extractable P, K, Ca, Mg, and Na

In the case of extractable phosphorus and potassium, whose levels depend a lot on the fertilization carried out, we believe this type of variation to be normal, since a greater application certainly corresponds to a greater consumption. These two nutrients are fundamental to the quality of the olive oil produced [58].

The registered variation in the extractable Ca and Mg content is, in our opinion, related to the pH corrections, using $CaCO_3$ or $MgCO_3$, to which the olive orchards in the super-intensive production system are frequently subjected to optimize the production conditions, which does not happen in traditional rainfed olive groves. The supply of Ca and Mg by these alkaline products counteracts the decrease in the levels of these elements caused by the consumption of plants and possible leaching. The Ca and Mg transported by irrigation water could also contribute to this result, namely in recent years, when the water carbonate content in the irrigation water increased substantially (from 64 to 98 mg L^{-1}) [23].

According to Abdel Kawy and Ali (2012) [59], the result obtained for extractable Na can be explained by the sodium transported by irrigation water. In our case, given that the water used for irrigation has an average content of 11.2 mg L^{-1} of Na (Table 1), and taking into account that the super-intensive olive grove receives, on average, 3000 m^3 ha^{-1} $year^{-1}$ (Table 2), this corresponds to a sodium input into the soil of approximately 33.6 kg of Na $year^{-1}$ ha^{-1}, which, in a highly controlled irrigation system and with reduced leaching, as well as due to the low natural rainfall, can lead to the accumulation of sodium in the soil.

These results coincide with other works carried out in the Mediterranean Basin, such as those by Bouaroudj et al. (2019) [22], Gonçalves and Martins (2015) [60], and Telo da Gama et al. (2019) [23]; these authors also highlight this result, stating that this is a result that deserves our utmost attention and should be constantly monitored, since, in their opinion, soil sodization in the Mediterranean Basin seems to be something inevitable, taking into account that the amount of precipitation in this region is insufficient to carry out an effective leaching of salts, and there is also the tendency for a sharp decrease in these precipitations, given the climate change scenario.

4.1.5. Extractable Cd, Cu, Fe, Zn, Pb, Ni, and Mn

The quantity of extractable heavy metals and semimetals in soil depends on the total content of the element, the adsorption capacity of the soil, and physicochemical factors such as the pH and redox potential, which control the balance between the adsorbed fractions and those of the soil solution [61]. As these elements are, in general, not applied in the form of fertilizers (nevertheless, the fertilizers could contain some amounts of these elements, although the application of these elements is not a goal of fertilization) and their concentration in phytopharmaceuticals, except for copper, is much reduced, the explanation for the variation in their content will be related to the natural conditions of the soil [62]. For example, in some Mediterranean soils, according to Jebreen et al. (2018) [63], rocks are composed of three main minerals: calcite with impurities of Mn, Fe, Zn, Co, Sr, Pb, Mg, Cu, Al, Ni, V, Cr, and Mo; dolomite with impurities of Fe, Mn, Co, Pb, and Zn; and aragonite with common impurities of Sr, Ba, Pb, and Zn. This could contribute to explaining these results.

In the case of Fe, a very important nutrient for olive trees [64], we found a substantial accumulation of Fe oxides in soils where the CO_3^{2-} concentrations were higher than 50%, possibly due to precipitation of this element. It is also important to note that the bioavailability of these elements is affected by many factors, including the pH, redox potential, SOM, CEC, macronutrient levels, available water content, temperature, etc., and therefore, the presence of water can have some influence on the bioavailability of these elements, namely because of their influence on the redox potential of the soil. In our results, this influence was not clear. Nevertheless, the heavy-metal content of the soil is far from the limits presented by Portuguese legislation (Table 5)

Table 5. Maximum value of heavy metals in soil, depending on soil pH, according to Portuguese legislation.

Parameter	**Maximum Value in Soil (mg kg^{-1})**		
	5.0 < pH < 6.0	**6.0 < pH < 7.0**	**pH > 7.0**
Cadmium	0.5	1	1.5
Copper	15	50	100
Nickel	20	50	70
Plumb	50	70	100
Zinc	60	150	200
Mercury	0.1	0.5	1
Chromium	30	60	100

4.2. Hedgerow Olive Orchards versus Other Irrigated Crops (Corn, Tomato, Cereals, Others)

4.2.1. pH

The soil alkalinization, common in arid and semi-arid climates, depends on factors such as the irrigation period, the volume of water applied, and the composition of the irrigation water, especially its balance of basic cations and bicarbonates, as well as the oxidation of organic compounds and ammonium ion nitrification [65]. In this particular case, since the water used for irrigation is of good quality (C1S1 or C1S2 according to the USDA classification), but with high levels of calcium, magnesium, and carbonates, this result can be easily explained. To this composition of irrigation water, which enhances alkalization, we can add a low annual precipitation that leads to a low leaching of basic cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}), thus meeting the conditions for an increase in pH values.

In olive orchards, the explanation for the result obtained, contrary to other irrigated crops, lies in the smaller quantity of basic cations introduced by the irrigation water (less amount of water applied) and in the acidification caused by the mineralization of soil organic matter, given that, as we will see below, this is the only crop with a significant reduction in this soil compound, and these facts are significantly correlated (data not presented in this work).

We can notice, in Table 4, that the initial pH value was higher in olive orchards. This fact is common in Mediterranean regions, where farmers select more alkaline soils to install olive orchards. This trend was completely reversed during the decade under analysis.

4.2.2. Electrical Conductivity (EC)

The EC values depend mainly on anthropic issues. Both fertilizers, used in larger quantities in irrigated agriculture, and the ions transported by irrigation water [66], even in good-quality irrigation water, as in this case, introduce high amounts of salts into the soil, leading to an increase in soil salinity [61]. This fact is particularly relevant in the soils of the Mediterranean Basin, where winter rainfall is insufficient to promote the leaching of excess salts. This is a particularly important aspect, given that about 25% of the soils in the Mediterranean Basin are salinized [67], putting the agricultural productivity of these regions at serious risk [68]. This phenomenon depends on irrigation water quality, soil geology, climate, physiographic position, and agricultural practices [69]. This same result was obtained by several authors such as Ayars et al. (1993) [70], who found that, after 6 years of continuous irrigation, the irrigated plots had a significantly higher EC than the rainfed plots, and that this result was more evident when the irrigation water used had a larger amount of salts.

In our results, we can also verify that the crops that received the highest volumes of irrigation water, such as corn, are those whose EC values have grown the most over a decade, which is in agreement with the consulted bibliography. It is also important to notice, as we can see in Table 4, that there is a close relationship between irrigation water consumption and the fertilizers used on the different crops. Therefore, a possible explanation for this variation in EC values may be a greater use of fertilizers on crops such as corn or tomatoes.

Nevertheless, Ferjani et al. (2013) [71] while working on clayey soils, reported a strong variation in EC throughout the year, decreasing from 8.40 dS m^{-1} in the summer to 2.00 dS m^{-1} in the winter. This decrease is due to salts that were washed away by the rain during this period.

4.2.3. Soil Organic Matter (SOM)

Maintaining soil organic matter levels in corn, tomato and cereal crops is of great importance for the sustainability of irrigation agroecosystems in the Mediterranean regions. For this result, it was very important to implement conservation agriculture practices, which began around 15 to 20 years ago in the region. Leaving the crop residues, after being destroyed, in the soil and the practice of no-tillage are thus giving visible results, contrary to the trend that occurred in previous decades in this same region and reported by Nunes (2003) [21].

This result is shared by several authors, namely Martinez-Mena et al. (2002) [72], who mentioned that, in the Mediterranean region, the practice of conservation agriculture, without tillage and the incorporation of crop residues, over 9 years, led to a 0.31-fold increase in SOM content, when compared to systems of conventional agriculture with tillage and the removal of crop residues. This result is very important, given that irrigation is generally seen as a technique that reduces SOM levels, as the water supplied during the hottest season of the year positively influences the mineralization process [47,73]. Our results proved that, in semi-arid climates, especially with conservation agricultural practices, as mainly occurs in maize and cereal production, it is possible to maintain this important soil compound. This last result was confirmed by the work of Álvaro-Fuentes et al. (2009) [74], who concluded, in a study carried out in a Calciorthid Xerollico with a clayey texture, in the region of Zaragoza, Spain, that if the cultural intensification is carried out in non-tillage systems, the SOM content can increase significantly. Of course, all these results are highly dependent on the type of soil, the volume of water used for irrigation, quality of irrigation water, and fertilization, but also on the climate and the initial content of SOM [48].

Several explanations can be found for the result obtained in the intensive olive orchards, which in-depth knowledge of the region's agricultural systems allows us to highlight. Firstly, the amount of residues produced in the olive grove is substantially lower than the residues produced in the aforementioned crops, and the practice of cover crops between the rows is recent. According to Lal (2005) [75], in the USA, corn, wheat, and tomato crops annually produce about 10.1, 5.0, and 5.0 Mg ha^{-1} $year^{-1}$, respectively, of organic residues, while in olive groves, if we remove pruning residues, a common practice until a few years ago, the amount of residues left in the soil will be less than 1 Mg ha^{-1} $year^{-1}$, clearly not enough to replace the organic matter that disappears through mineralization [76]. As previously mentioned, this scenario tends to be inverted due to the practices of conservation agriculture implemented in recent years, which foresees the incorporation into the soil of the pruning residues and the herbaceous vegetation existing between the rows—cover crops.

4.2.4. Extractable P, K, Ca, Mg, and Na

The results obtained for extractable P, which may indicate an over-fertilization with this nutrient, are particularly evident in crops that receive larger amounts of fertilizers, namely in corn and tomato crops, as mentioned above. This fact is mentioned in the work by Monteiro and Torent (2010) [77], where they mention that over-fertilization with phosphorus has been happening in the Mediterranean Basin, and the work by Butusov and Jernelov (2013) [78], who also mention the environmental risks of this practice.

In the case of extractable potassium, the anthropogenic influence is also the main influence on the levels of these nutrients. An adequate potassium content in plants is of enormous importance for the adequate control of transpiration and for increasing the efficiency of water use in irrigation, and should be one of the nutrients monitored in these production systems [79].

It should be noted that, according to the soil nutrient content classification produced for the Egner–Riehm extraction method [32] (0–25 mg kg^{-1}—very low; 25–50 mg kg^{-1}—low; 50–100 mg kg^{-1}—medium; 100–200 mg kg^{-1}—high; and > 200 mg kg^{-1}—very high), the laboratory method used in this work, extractable phosphorus and potassium contents are always presented as high and very high, thus not constituting, in general, any obstacle to the productivity of the plants.

In the case of Ca and Mg, we emphasize the enormous increase in the concentration of calcium in the soil, significant in statistical terms, observed in the tomato crop. This result is explained by the supplementary application of calcium to this crop as a way of reducing the risk of tomato apical rot. The explanation for the results obtained on soil-extractable Na lies mainly in the sodium transported by the irrigation water, and this same fact has been stated by Bouaroudj et al. (2019) [22]. This result was also verified in studies conducted by Belaid et al. (2010) [80], who found that, after 15 years of continued irrigation, the physical properties of the soil were degraded due to the increase in sodium content in the soil, which was particularly evident when water with a higher sodium content was used.

In our study, we found a greater increase in sodium levels in olive and cereal crops and, although equally significant, a smaller increase in corn crops. On the one hand, since the corn crop receives the largest volume of irrigation water, applied almost always using sprinkler irrigation, we believe that the amount of sodium supplied to the soil by the irrigation water would be greater, but, on the other hand, this volume of water will also have led to some leaching of salts, which did not happen, for example, in olive groves, where drip irrigation provides a much greater control over the amount of water supplied and, consequently, a greater irrigation efficiency. We already found a similar result when we analyzed the EC of soils occupied with traditional olive groves versus hedged olive groves, for exactly the same reasons.

5. Conclusions

We conclude that, compared with traditional olive groves, the implementation of hedgerow olive systems induced changes to several soil chemical properties, leading to soil chemical degradation processes such as a loss of organic matter and acidification, but not causing salinization. Soil sodification happens significantly in both production systems; nevertheless, the increase was about 33% in hedgerow olive groves and just 10% for rainfed olive ones. The extractable Cu, Fe, and Ni increased significantly in hedgerow olive groves, while in the traditional olive groves, the extractable Cu and Fe did not show any statistical difference in the period under analysis. The Ni decreased significantly, which could be attributed to decreases in soil pH and organic matter.

Unlike the other irrigated crops analyzed (corn, tomato, and cereals), the hedgerow olive grove led to a significant decrease in the soil pH and SOM content. Regarding the electrical conductivity and extractable sodium content, the increase in both parameters was generalized among various crops, and there were no significant differences between the crops analyzed.

Therefore, our results suggest the need to implement conservation agriculture practices in hedgerow olive groves to achieve sustainability and viability in this production system. Nevertheless, further research is needed to establish the systematic monitoring of not only soil chemical properties, but also physical and biological properties, which will help to reduce uncertainties about the risks and impacts of introducing hedgerow olive grove systems.

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