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# Impacts of Fertilization on Environmental Quality across a Gradient of Olive Grove Management Systems in Alentejo (Portugal)

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**Abstract:** Olive groves are Mediterranean socioecological systems. In Portugal (350,000 hectares of olive groves), a transition is ongoing towards intensification. Such effects may arise from the incremental use of agrochemical fertilizers. The Alentejo region, Portugal, was stratified according to the olive management systems (i.e., extensive groves managed conventionally, integrated or organically, and intensive and highly intensive farms) and erosive states. Agronomic (i.e., fertilizers) and biological (i.e., herbaceous and lepidopteran richness and biodiversity) variables were quantified in 80 plots so we could know how managements affect biodiversity. Intensive and highly intensive farms showed the highest erosion (up to 48 t $ha^{-1}$ $year^{-1}$) and the highest concentration of nitrates (11–16 ppm), phosphates (8–15 ppm), and potassium (169–183 mg $kg^{-1}$), aligned with its lower flora (null) and fauna (0.50–1.75 species). Conventional extensive farms attained an intermediate position, and integrated and organic managements showed the lowest erosion (up to 20 t $ha^{-1}$ $year^{-1}$), and the lowest concentration of nitrates (5–6 ppm), phosphates (2–4 ppm), and potassium (92–125 mg $kg^{-1}$) aligned with its higher flora (14–27 species) and fauna (up to 8 species). Studies aimed at characterizing the multifunctionality of olive groves are essential in Portugal, also considering how soil practices can minimize externalities driven by rapid changes in crop systems.

**Keywords:** agricultural intensification; biodiversity; biostatistics; chemical fertilizers; ecology; soil erosion; multifunctional agriculture; olive groves



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## 1. Introduction

Agricultural systems cover 175 million hectares (M ha) in Europe, or 40% of the total land area, with the area devoted to olive groves covering 5 M ha [1]. Olive groves are especially relevant in southern Europe, exceeding 2.82 M ha in the Iberian Peninsula, thus shaping iconic and valuable rural landscapes [2,3]. Spain has an olive-growing area of more than 2.5 M ha with multiple land and agricultural regulations governing these crops, including the Olive Grove Law (Ley del Olivar) and the Andalusian Olive Grove Master Plan (Plan Director del Olivar Andaluz) [4,5]. In Portugal, olive groves are a fast-expanding crop with more than 352,000 ha, and 51% of this area is concentrated in Alentejo [6,7].

In Portugal, olive groves are crops with a strong potential for multifunctionality, highlighting their economic function, which contributes up to 1.36% of farm income [7]; their social function, as they foster generations of both family and external employment [8]; and their environmental function, as they are reservoirs of agrobiodiversity, constituting habitats for 17% of the Iberian flora and approximately 25% of the birds and insects [9,10]. Olive groves are therefore considered scientifically as socioecological systems that potentially provide multiple ecosystem services (ES). These include provisioning (e.g., table olives and olive oil, with more than 76,200 tons of olive oil per year) (average data from the 2009–2015 campaigns in Portugal [11]); regulating (e.g., mitigation of erosion processes and atmospheric $CO_2$ sequestration, among others [12]); and cultural (e.g., olive tourism and rural development) ES [13–15].

Despite the relevance of olive groves in the Mediterranean region, they are currently in a situation of productive and economic vulnerability due to the low income rate of many farms, especially family and marginal ones, a vulnerability that hampers the long-term sustainability of these crops [16]. This vulnerability has been increasing for decades, driven by two factors: (1) the migration of the rural population to urban areas, resulting in a lack of labor and generational renewal, leading to the abandonment of marginal, remote, and least productive rural areas [17]; and (2) the entry into force of the Common Agricultural Policy (CAP), a policy which was first started in 1957, and which although it currently includes resilient agriculture and rural development measures, for many past decades focused on the productive dimension of rural areas, disregarding their environmental one, thus partly driving the collapse of traditional olive farms [18,19]. In order to alleviate the economic vulnerability of Mediterranean olive groves, crops have either been abandoned, due to their low financial profitability, or intensified, to increase their productivity by increasing plant densities, technification, and application of energy, irrigation, and agrochemical inputs (i.e., herbicides, pesticides, and fertilizers) [18,20,21]. While rural land abandonment leads to an increase in land scrubbing and an erosion of social and territorial cohesion [22], a rapid and unsustainable trend towards intensification may likely lead to an increase in soil erosion, landscape homogenization, and diffuse pollution, all of which negatively impact the multifunctionality and sustainability of olive groves and associated landscapes [20,21,23].

In the Portuguese region of Alentejo (southern Portugal), where olive groves have been expanding, they now exceed 179,000 ha. In this region, there are multiple management systems that can be classified according to multiple criteria, such as crop plant density or agronomic and soil management practices (e.g., type of fertilizer application and herbaceous plant cover) [24,25]. Olive groves have traditionally been managed conventionally and extensively (up to 200 trees ha$^{-1}$), where the use of chemical fertilizers is not regulated and the use of machinery is conditioned to the slope of the land (only in slopes of less than 20%) [24]. However, in recent years, alternative management methods such as integrated and organic have emerged to improve agricultural multifunctionality. The integrated management allows the growing of partial herbaceous covers, either natural or planted, with a predominance of grasses, leguminous, or cruciferous species due to their mitigating effect on soil erosion processes, and the use of chemical fertilizers is allowed in a controlled manner by external agencies. In contrast, the organic management systems allow the presence of living or inert plant cover and organic fertilizers, which results in greater soil fertility rates and a reduction in diffuse pollution [26,27]. These management methods are typically rainfed, but they also fit with deficit irrigation systems (i.e., water addition of up to 1500 m$^3$ ha$^{-1}$ year$^{-1}$ focusing on periods with hydric stress) [20,25]. This is particularly important in Alentejo, a region with a Mediterranean climate where, paradoxically, water resources have not lately been considered as a constraint to agricultural development. This is the consequence of the Alqueva reservoir, with a surface area of 250 km$^2$ and a capacity of 4150 Hm$^3$, which has been considered as an almost inexhaustible source of water [28,29].

In addition, the three olive management systems considered here (conventional, integrated, and organic) can include different plant densities, ranging from extensive (around 200 trees ha$^{-1}$) to intensive (200–800 trees ha$^{-1}$) and highly intensive (800–2000 trees ha$^{-1}$) [24,25]. Conventional extensive, intensive, and highly intensive managements are common in Alentejo, with the typical removal of the herbaceous plant cover by using herbicides or plowing and additionally using chemical fertilizers in an uncontrolled manner (i.e., fertilizers with nitrogen, phosphorus, and potassium, NPK) so that olive trees are not affected by intraspecific competition that limits their growth or productivity [30,31]. However, the use of these chemical fertilizers must be regulated, as their application, which may be in the form of foliar fertilization or fertirrigation (i.e., incorporated in irrigation water), can cause cumulative toxicity in the agricultural and food production chain, with harmful health consequences for consumers [32]. On the other hand, the indiscriminate use of agrichemical products has multidimensional impacts on crops, with a greater risk of diffuse pollution at a landscape scale due to the movement of pollutants through surface- and groundwater [33], as well as direct impacts on agrobiodiversity. To monitor such impacts, organisms such as some herbaceous plants and lepidoptera can be used as bioindicators of environmental quality [10,21,34,35].

The main objective of this study is to assess the multifunctionality of the different management systems currently applied to olive groves [36]. To achieve this, the following specific objectives were set: (1) to characterize the olive-growing areas of Alentejo (Portugal) based on environmental impacts, with a focus on soil erosion and chemical fertilizers; (2) to check the interconnection between soil erosion and the amount of agrochemical inputs applied to maintain the productivity rates; and (3) to check the influence of chemical fertilizers on plant and lepidopteran richness and diversity in each management model and estimated erosive state, thus rendering such indicators as bioindicators of environmental quality.

## 2. Materials and Methods

### *2.1. Study Area*

The Alentejo region (territorial unit NUTS-II, in southern Portugal) was selected as case study area (Figure 1).

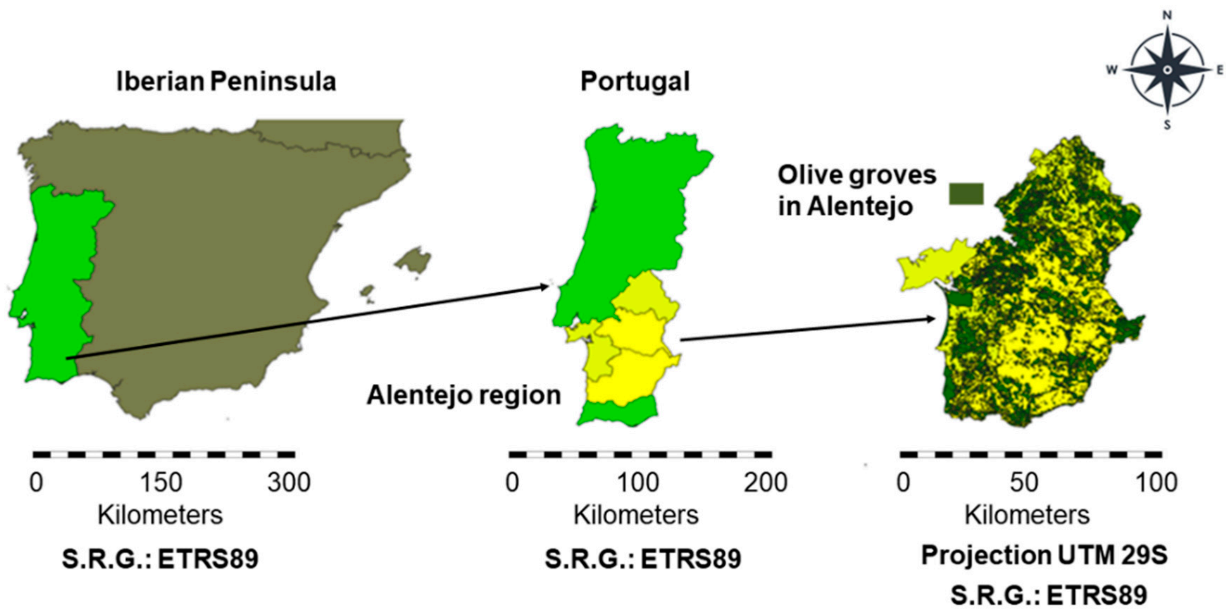


**Figure 1.** Geographical location of the study area and distribution of olive groves.

In this region, a Mediterranean climate predominates, with an average annual rainfall of 450–750 mm, dry summers with average temperatures between 24–28 °C, and wet winters with temperatures ranging between 8–11 °C [7,37]. Although Alentejo accounts for approximately 51% of the national olive-growing area in Portugal, exceeding 179,000 ha [6], these crops have not until very recently become monocultures of significance at regional level, with traditional olive groves having instead historically been components of heterogeneous, complex, and multifunctional landscape mosaics formed by agricultural systems, alongside holm oak (*Quercus ilex*, L. 1753)- and cork oak (*Quercus suber*, L. 1753)-dominated silvopastoral systems, nationally known as Montados [38]. However, it is important to highlight the relevance, in socioproductive terms, of the olive groves at the regional level, which generate an average value of approximately 237,912 tons (t) of olive oil per year (data corresponding to the 1995–2020 campaigns [39]), as well as contributing to the generation of 53% of rural employment in the area [40].

Specifically, olive groves in Alentejo are located at altitudes of 200–600 m above sea level (masl). Much of the region is formed by soils derived from intrusive igneous (mainly granites) and metamorphic rocks (mainly schists), with soils up to 150 cm deep and variable slopes of up to 15%. These soils have a loamy or sandy-clay loam texture that contributes to an increase land capability for agriculture and forestry [7]. Furthermore, other regional soils exist that are developed over calcareous materials, with a high limestone content, that are more susceptible to erosion due to the absence of fine soil particles that can act as soil stabilizing agents [41,42].

Olive farms in Alentejo operate under diverse management systems, with a gradient of agricultural intensification (in terms of plant density) largely increasing from north to south. In this sense, olive farms can be managed extensively, with plant densities up to 200 trees ha$^{-1}$, embracing largely conventional and integrated systems, where the addition of chemical fertilizers is allowed but controlled, as well as organic and biodynamic systems, where only natural fertilizers are allowed [24,25]. In these extensive olive groves, partial or total herbaceous vegetation covers are usually implemented to mitigate soil erosion risk [26,27]. In addition, there are also higher-density olive plantations, including intensive and highly intensive groves (i.e., 200–800 trees ha$^{-1}$ or 800–2000 trees ha$^{-1}$ respectively) [24,25,43]. Agricultural intensification is rapidly occurring where either of the following two factors occur: (1) access to the irrigation network dominated by the Alqueva reservoir [6,44]; and (2) a high amount of energy and agrochemical inputs (i.e., fertilizers, pesticides) applied to the crops [25,43]. Although most intensive olive groves in the region incorporate a herbaceous plant cover, it is still possible to find conventional, and largely intensive, crops where the herbaceous cover is removed and chemical fertilizers are used indiscriminately, bearing environmental impacts on biodiversity and greater soil degradation rates in the long term [18,21–23,33].

### *2.2. Experimental Design and Sample Collection*

We used geospatial sources such as CORINE Land Cover and Epic WebSIG-Portugal [45,46] to stratify our case study region according to two criteria: (1) olive tree management systems (i.e., extensive olive groves up to 200 trees ha$^{-1}$, including conventional, integrated, and organic crops as well as conventional intensive (200–800 trees ha$^{-1}$) and conventional highly intensive farms (800–2000 trees ha$^{-1}$); and (2) soil erosion states according to the Universal Soil Loss Equation (USLE) [47,48] (Equation (1)):

$$A = R \times K \times LS \times C \times P \tag{1}$$

where $A$ is the potential annual soil loss (t ha$^{-1}$ year$^{-1}$); $R$ is the rainfall erosivity (J ha$^{-1}$); $K$ is the soil susceptibility to erosion or soil erodibility (Mg J$^{-1}$); $LS$ is the length and degree of the slope (dimensionless and in %); $C$ is the soil plant cover (dimensionless); and $P$ is the factor of implementation of the soil conservation agricultural practices (dimensionless).

To calibrate the USLE equation for Alentejo, bibliographic sources and experimental data were used. For the estimation of R (rainfall erosivity) and LS (length and degree of slope) factors, bibliographic criteria were consulted, selecting the methodologies developed by Moreira-Madueño in Andalusia and Rodríguez Sousa et al. in Alentejo [7,49]. The soil erodibility (K factor) was estimated experimentally following the criteria by Gisbert Blanquer et al. [50], where the susceptibility of the soil to be eroded is estimated based on the Wischmeier and Smith nomograms, considering soil texture, structure, and permeability as the inputs. In a nutshell, the higher the concentration of silt and sandy soil particles (0.50 μm to 2 mm) and the lower the amount of organic matter in the soil, the less stability it has and thus the more susceptible it is to soil erosion [51,52].

Soil plant cover factor C was calibrated following Gómez et al. [53], which varies according to three structural aspects: (1) distance between olive trees (planting frames and distance between trunks, whereby the maximum is in the extensive olive groves and the minimum is in the intensive and highly intensive olive groves); (2) radius of the tree canopy, a factor related to the age and varieties of olive trees (and is generally the maximum in extensive olive groves and the minimum in highly intensive crops); and (3) extent of herbaceous plant cover, which can be null, partial, or total. Applying these considerations resulted in a C factor of 0.25 for the conventionally managed extensive olive groves, where the planting frame is between 7 × 7 and 8 × 8 m [53,54] and trees are frequently older than 50 years old and have a radius of approximately 2.5 m, with partial but sparse vegetation herbaceous cover [6,7]. For the extensive integrated olive groves, the structural characteristics described above are maintained, with only vegetation cover being more abundant than in extensive conventional groves, ultimately resulting in a C factor of 0.16. For extensive organic olive groves, the most significant change is the predominance of a total plant cover [26,43], maintaining the distance between trees and their diameter with a C factor of 0.06.

For the conventionally managed intensive olive groves, the C factor increased to a value of 0.41 due to the scarcity of vegetation cover and the presence of young trees (<10 years) considering a radius of 1 m and planting frames of 6 × 3 m [24]. Finally, highly intensive and conventional olive groves share some common characteristics with intensive olive groves, with even younger trees (up to 2 years old), a smaller radius, and planting frames up to 2 × 2 m, resulting in a C factor of 0.50 [7,43]. In relation to the P factor, a value of 1 was assumed for all densities and management systems, since in Alentejo there are no farms in terraced slopes, and tillage practices are only applied at tree lines to control herbaceous vegetation [7,53,55].

The USLE equation was estimated quantitatively following the approach by Rodriguez Sousa et al. [7], where soil losses were estimated for the following types of olive groves: extensive olive groves managed either conventionally, integrated, or organically, and intensive and highly intensive olive groves under conventional management (Table 1). In this sense, the study area was stratified into different levels: (1) null erosion, which is mathematically possible in flat land, although soil is considered to be physically affected by erosion even if such impact is residual; (2) slight erosion (slopes up to 3%); (3) moderate erosion (slopes up to 7%); and (4) severe erosion (slopes up to 15% and higher).

Assuming a constant regional rainfall erosivity value of 95, in line with Santisteban et al. [56], erosion levels varied essentially according to soil erodibility (factor K) and plant cover (factor C), reaching higher soil erosion rates in intensive and highly intensive management systems, with minimal erosion in groves that are organically managed. According to our spatial stratification of the territory, five types of olive groves (combinations of plant densities and management systems), with four erosive states each, were identified, giving rise to 20 different agronomical treatments. For each treatment, a simple random sampling was established, selecting 4 plots as sampling points, obtaining a final sample size of $n = 80$ plots (Figure 2).

In each selected plot, a transect of 1 km (km) in length was established where three soil samples were taken using a 5 cm height steel core (volume: 141.372 $cm^3$). These samples were then dried for 24 h at 105 °C and then sieved using a 2 mm mesh to obtain the soil fine fraction [27,36]. The concentration of nitrates, phosphates, and potassium in the fine fraction was determined and considered as indicators of diffuse soil contamination. The concentration of nitrates ($NO_3^-$) was determined using colorimetry (nitrate ions are reduced to nitrite ions in the presence of a reducing agent which results in a color change in the sample) [7,57]. Phosphates ($PO_4^{3-}$) were estimated using spectrophotometry, by applying a standard additions method, quantifying the light absorption of the sample in the ultraviolet–visible range, at a wavelength of 420 nm [58]. Lastly, the concentration of potassium ($K^+$) was quantified using flame photometry [59].

**Table 1.** Erosion estimation (A, t ha$^{-1}$ year$^{-1}$) for each type of olive grove sampled, specifying planting densities and management systems, where R: rainfall erosivity (J ha$^{-1}$); K: soil erodibility (Mg J$^{-1}$); LS: length and degree of slopes (dimensionless and in %); C: soil cover (dimensionless); and P: conservation practices (dimensionless).

| Type of Olive Grove | | Erosion Level | USLE Factors | | | | | A |
|---|---|---|---|---|---|---|---|---|
| Plant Density | Management System | | R | K | LS | C | P | |
| Extensive (up to 200 trees ha$^{-1}$) | Conventional | Null | 95 | 0.52 | 0.00 (0%) | 0.25 | 1 | — |
| | | Slight | 95 | 0.52 | 0.15 (3%) | 0.25 | 1 | 2.24 |
| | | Moderate | 95 | 0.68 | 0.70 (7%) | 0.25 | 1 | 11.37 |
| | | Severe | 95 | 0.52 | 2.20 (15%) | 0.25 | 1 | 27.03 |
| | Integrated | Null | 95 | 0.60 | 0.00 (0%) | 0.16 | 1 | — |
| | | Slight | 95 | 0.54 | 0.15 (3%) | 0.16 | 1 | 1.47 |
| | | Moderate | 95 | 0.73 | 0.70 (7%) | 0.16 | 1 | 7.81 |
| | | Severe | 95 | 0.61 | 2.20 (15%) | 0.16 | 1 | 20.29 |
| | Organic | Null | 95 | 0.58 | 0.00 (0%) | 0.06 | 1 | — |
| | | Slight | 95 | 0.57 | 0.15 (3%) | 0.06 | 1 | 0.49 |
| | | Moderate | 95 | 0.58 | 0.70 (7%) | 0.06 | 1 | 2.31 |
| | | Severe | 95 | 0.60 | 2.20 (15%) | 0.06 | 1 | 7.52 |
| Intensive (200–800 trees ha$^{-1}$) | Conventional | Null | 95 | 0.44 | 0.00 (0%) | 0.41 | 1 | — |
| | | Slight | 95 | 0.56 | 0.15 (3%) | 0.41 | 1 | 3.93 |
| | | Moderate | 95 | 0.45 | 0.70 (7%) | 0.41 | 1 | 12.38 |
| | | Severe | 95 | 0.34 | 2.20 (15%) | 0.41 | 1 | 30.05 |
| Highly intensive (800–2000 trees ha$^{-1}$) | Conventional | Null | 95 | 0.46 | 0.00 (0%) | 0.50 | 1 | — |
| | | Slight | 95 | 0.48 | 0.15 (3%) | 0.50 | 1 | 3.42 |
| | | Moderate | 95 | 0.47 | 0.70 (7%) | 0.50 | 1 | 15.63 |
| | | Severe | 95 | 0.46 | 2.20 (15%) | 0.50 | 1 | 48.07 |

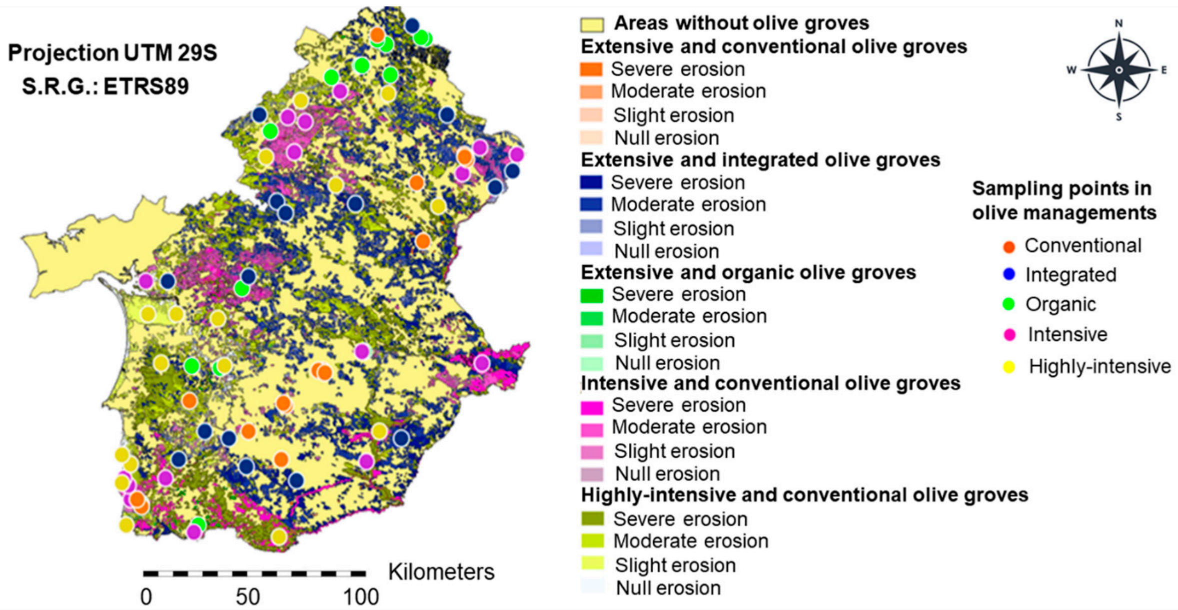


**Figure 2.** Sampling design (sampling points) carried out in the study area according to the existing types of olive groves (plant densities and management systems) and erosive states calibrated through the USLE equation.

Following indications by Gómez et al. [60], the vegetation in each plot was identified for 10 square plots of 25 × 25 cm placed every 100 m along the 1 km transect. In each of these square plots, the percentages of bare soil and herbaceous and woody plant cover were visually estimated and considered as indicators of soil protection. The average richness of the total plant cover, with cover vegetation that contributes to the control and mitigation of soil erosive processes such as grasses, crucifers, and legumes (which also contribute to nitrogen fixation in soil) [61,62], was also independently estimated. The herbaceous diversity (including all herbaceous plants) was calculated for each plot using Shannon's index [63] (Equation (2)):

$$H^{'} = \sum pi \times log_2\, pi \tag{2}$$

where $H'$ is the Shannon diversity (bits, information theory units defined as the number of equiprobable decisions for a given event to occur) and *pi* is the relative abundance of each species.

Finally, lepidoptera (i.e., diurnal butterflies) richness and diversity (*Lepidoptera*: *Papilionoidea* Latreille, 1802) were measured along the transects in each plot following the Butterfly Monitoring Scheme (BMS) protocol along the selected transect. This task included the passive visual (i.e., without removing vegetation) counting and identification of adult individuals [64]. Lepidoptera are considered as bioindicators of the quality of agricultural systems due to their extreme sensitivity to pollutants,

### 2.3. Statistical Analysis

Following the descriptive analysis (i.e., mean values and standard deviations) of the variables considered as environmental quality indicators (i.e., soil fertilizers and bioindicators of fauna, related to diurnal lepidoptera, and of flora, related to percentages of plant cover and richness and diversity of herbaceous plants), their normality and homoscedasticity were tested using the Shapiro-Wilk and Levene tests [65,66]. Depending on the nature of the data, the possibility of significant differences for the dependent variables mentioned above between the treatments (i.e., erosion levels and olive grove management systems categorized for the study area) was checked by means of an analysis of variance (ANOVA) or a Kruskal-Wallis H-test in the case that the residual of the models were not normally distributed [67]. If significant differences were detected for any of the dependent variables, a Tukey-Kramer post-hoc test was performed to generate a matrix of homogeneous subgroups to identify significant differences between groups [68]. In addition, multiple linear regression models were performed to check whether any specific soil fertilizer had a greater influence on the bioindicators analyzed (i.e., richness and diversity of lepidoptera and herbaceous plants, specifically differentiating the richness of grasses, legumes, and cruciferous), and we additionally tested the possible interactions between the various independent variables considered (i.e., fertilizers) [69]. All statistical analyses were carried out using the IBM SPSS Statistics software [70] considering a significance level of $\alpha = 0.05$.

## 3. Results

### 3.1. Agrochemical and Biological Indicators

All the variables analyzed (i.e., chemical fertilizers and biological variables) showed a nonparametric character, resulting in highly significant values (i.e., $p$-value < 0.001 ***) in the Shapiro-Wilk and Levene tests. Combining non-normal and heteroscedastic variables, nonparametric statistical tests were implemented (Kruskal-Wallis H-test), finding highly significant differences ($p$-values < 0.001 ***) in all variables for at least one of the treatments considered (see specific results in Online Resource 1). To discern which treatments showed a different behavior for each variable, the descriptive statistical results for each parameter were analyzed, with results described in the subsections below. In parallel, a Tamhane post-hoc test was applied for the generation of homogeneous subsets.

#### 3.1.1. Chemical Fertilizers

Figure 3 shows, graphically, the concentration (mean and standard deviation) of $NO_3^-$, $PO_4^{3-}$, and $K^+$ in each of the management systems and the erosion levels considered, along with the results of the Tamhane post-hoc test implemented for the elucidation of homogeneous sets. This was all implemented by accounting for the existence of highly significant differences ($p$-value < 0.001 ***) for all fertilizers between case studies (see specific results in Online Resource 2).

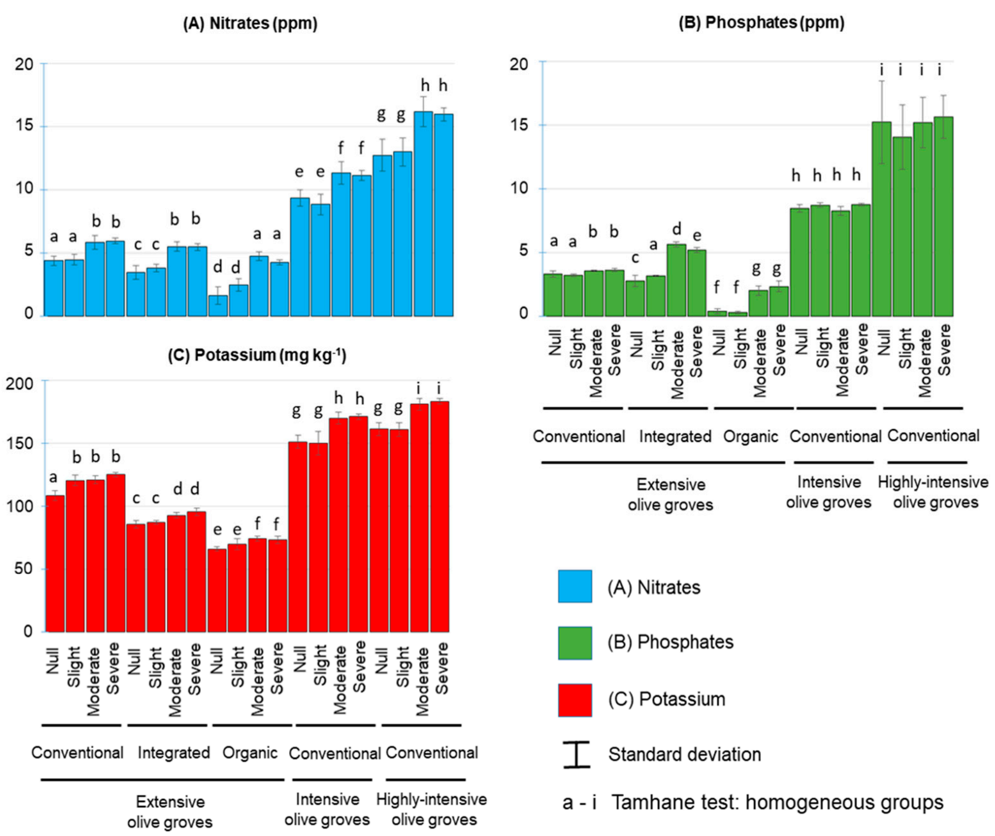


**Figure 3.** Mean values and standard deviations for each soil fertilizer: (**A**) nitrates (ppm); (**B**) phosphates (ppm); and (**C**) potassium (mg kg$^{-1}$) for each soil erosion level and type of olive grove. Indexes, a–i, indicate the classification groups generated in the Tamhane post-hoc test to establish similar categories.

Regardless of the olive grove management system, a higher concentration of chemical fertilizers on the soils was observed in alignment with the higher soil erosion rates. Increases were of up to 262.34% for $NO_3^-$, 187.77% for $PO_4^{3-}$, and 113.62% for $K^+$ in the plots with severe erosion as compared to plots with null erosion rates. On the other hand, by comparing severe erosive states and considering that the plots with these problems are those with the highest concentration of chemical fertilizers, results from opposite management systems in terms of fertilizer application indicated how differences between organically managed extensive olive groves and conventional highly intensive ones showed increases of 375.52%, 663.13%, and 250.16% in N, P, and K fertilizers in the most intensive crops.

Despite the existence of statistically clustered categories of olive groves according to the application of fertilizers, the post-hoc test did not show a uniform distribution for the variables considered. In general, within each olive management system, the moderate and severe erosion states were grouped differently with respect to the plots with null or slight erosion rates, thus corroborating the descriptive results whereby soil loss was directly correlated with the addition of chemical inputs to the crop. On the other hand, when analyzing olive grove management systems as a whole, extensive and organic agriculture came clear as a statistically differentiated type in the plots with low erosion, presenting a very scarce demand for N, P, and K fertilizers. In the same way, extensive, conventional, and integrated olive groves were characterized by intermediate contribution of fertilizers, resulting in distinct groups from plots with intensification practices, where the use of chemical fertilizers is maximized, resulting in higher erosion levels.

### 3.1.2. Lepidoptera Richness and Diversity

There were significant differences encountered for both the Lepidoptera richness and diversity indexes, estimated according to the Shannon Index, between the diverse olive grove management systems and related erosion levels (Figure 4; see specific results in Online Resource 3). The results showed a maximum value of 8.25 species for the null erosion level in organic farms and a minimum value of 0.50 species for highly intensive farms.

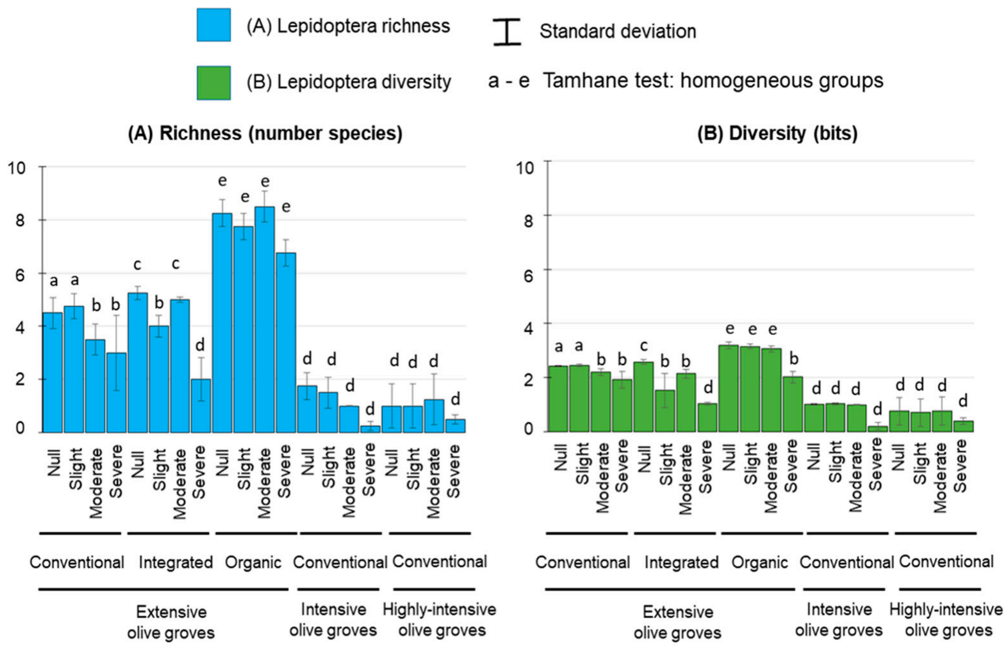


**Figure 4.** Mean values and standard deviations for lepidoptera richness (**A**, number of species) and diversity (**B**, bits) synthesized for each erosion level and type of olive grove. Indexes, a–e, indicate the classification groups generated in the Tamhane post-hoc test to establish similar categories.

A decrease was detected of up to 96.97% in lepidopteran richness between the most and least eroded plots, without even considering olive management systems. However, such a decrease was of 99.88% when comparing the extensive organic farms and highly intensive conventional olive groves in plots with null erosion levels (i.e., extreme opposed systems in terms of plant density and use of agrochemicals), thus indicating areas where soil loss does not necessarily bear negative consequences for biodiversity. The diversity of diurnal butterflies decreased by 87.78% between plots with null and severe erosion rates, and by 76.18% when comparing extensive and organic groves and highly intensive olive groves in the absence of erosion processes. Statistically, a differentiated group of intensive and highly intensive olive orchards was observed. In such plots, lepidopteran richness and diversity were sharply reduced regardless of soil erosion, and specimens were identified mainly belonging to *Pieris brassicae* (L., 1758), a butterfly with a highly generalist character. Integrated and conventional plots (i.e., extensive farms) showed a mixed distribution where the presence of *Pontia daplidice* (L., 1758) and *Aporia crataegi* (L., 1758) stood out. Finally, extensive and organic plots were, as expected, characterized by a greater richness and diversity of butterflies, and in addition to the aforementioned species, specimens of *Maniola jurtina* (L., 1758) and *Callophrys rubi* (L., 1758) were also observed.

### 3.1.3. Soil Cover, Richness and Diversity

Significant differences were detected for all the variables in at least one of the sampled treatments. Descriptive results for the percentages of plots with bare soil and plant cover are synthesized in Figure 5 (see specific and statistical results (i.e., Tamhane post-hoc test) in Online Resource 4).

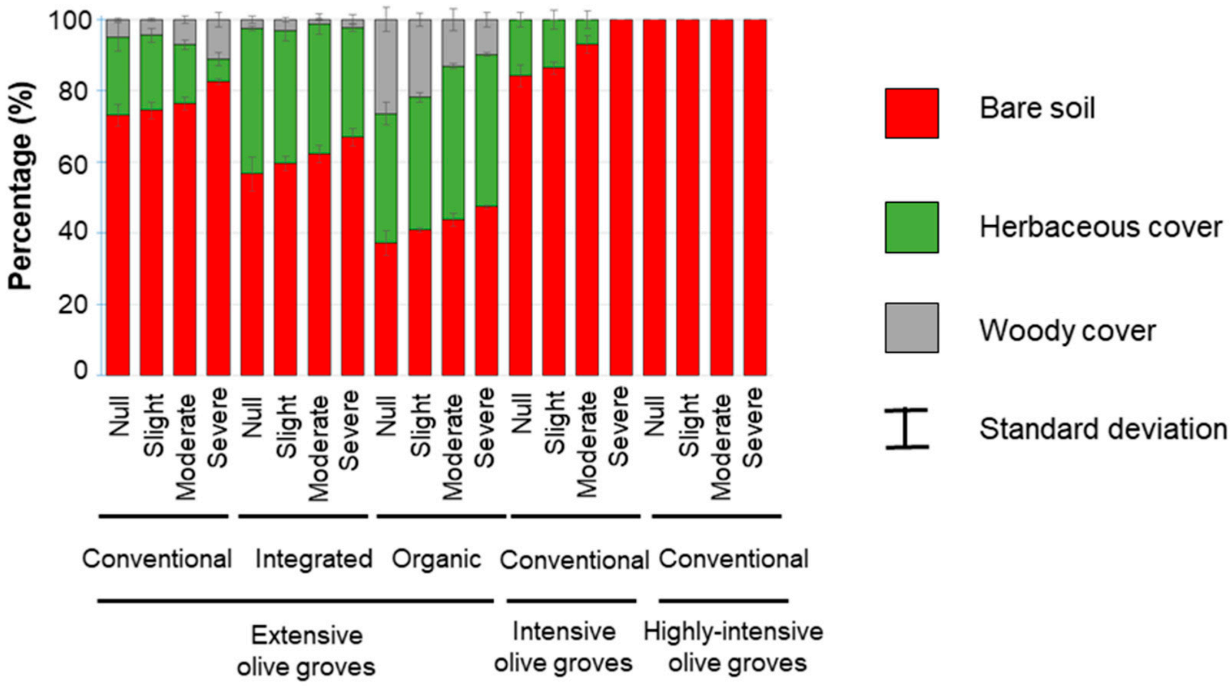


**Figure 5.** Mean values and standard deviations for plant cover (i.e., bare soil, herbaceous and woody covers) synthesized for each erosion level and type of olive grove.

It was observed how, in terms of soil cover, the percentage of bare soil reached a value of 100% for the severe erosive stages detected in intensive olive groves, and also across all types of highly intensive ones. Maximum values of plant cover were reached in extensive and organic farming (less amount of bare soil), showing values of between 35–40% herbaceous cover and 10–20% woody cover. In general terms, extensive and integrated farms were found to be the agricultural systems with the lowest percentage of bare soil, followed by conventionally managed crops. Intensive olive groves with severe erosion, and plots across all the erosive states in highly intensive olive groves, showed similar levels regarding the percentage of bare soil, herbaceous, and woody vegetation. This type presented the maximum percentage of bare soil (100%), consistent with null percentages of plant cover. Similarly, it was found that the lower the percentage of vegetation cover in the extensive conventional, integrated, and organic olive groves, the higher the rates of soil erosion.

As can be seen in Figure 6 (see specific results in Online Resource 5), herbaceous richness and diversity reached maximum values in the organically managed extensive plots, where the most abundant species were *Vicia sativa* (L., 1753), *Festuca indigesta* (Boiss., 1838), *Bromus hordeaceus* (L., 1753), *Trifolium arvense* (L., 1753), and *Carduus pycnocephalus* (L., 1763). In contrast, null values of diversity and richness were detected in intensive and highly intensive plots (conventionally managed). Finally, a higher richness of grasses and legumes was observed in integrated and extensive olive groves (i.e., more than three species in plots without erosion), whilst a higher richness of crucifers (i.e., up to four species) existed in plots under extensive and conventional management systems.

Regarding herbaceous richness and diversity, and disregarding erosive states, conventionally managed intensive and highly intensive farms could be clustered in a single group with no species. In contrast, the rest of the extensive olive groves showed a heterogeneous behavior, with organic farming standing out due to increased biodiversity resulting from the increased use of plant cover and lack of synthetic herbicides. Finally, when independently analyzing the richness of the grasses, legumes, and crucifers, where the typical species were *Festuca indigesta* (Boiss., 1838), *Vicia sativa* (L., 1753), and *Diplotaxis erucoides* (DC., 1821), intensive and highly intensive plots showed null values for these variables, whilst plots under extensive management showed heterogeneous statistical patterns. Within extensive olive groves, a greater richness for these species could be generally detected in the plots with integrated olive groves (except for cruciferous, which prevailed in organic plots, and also in specific plots with conventional management).

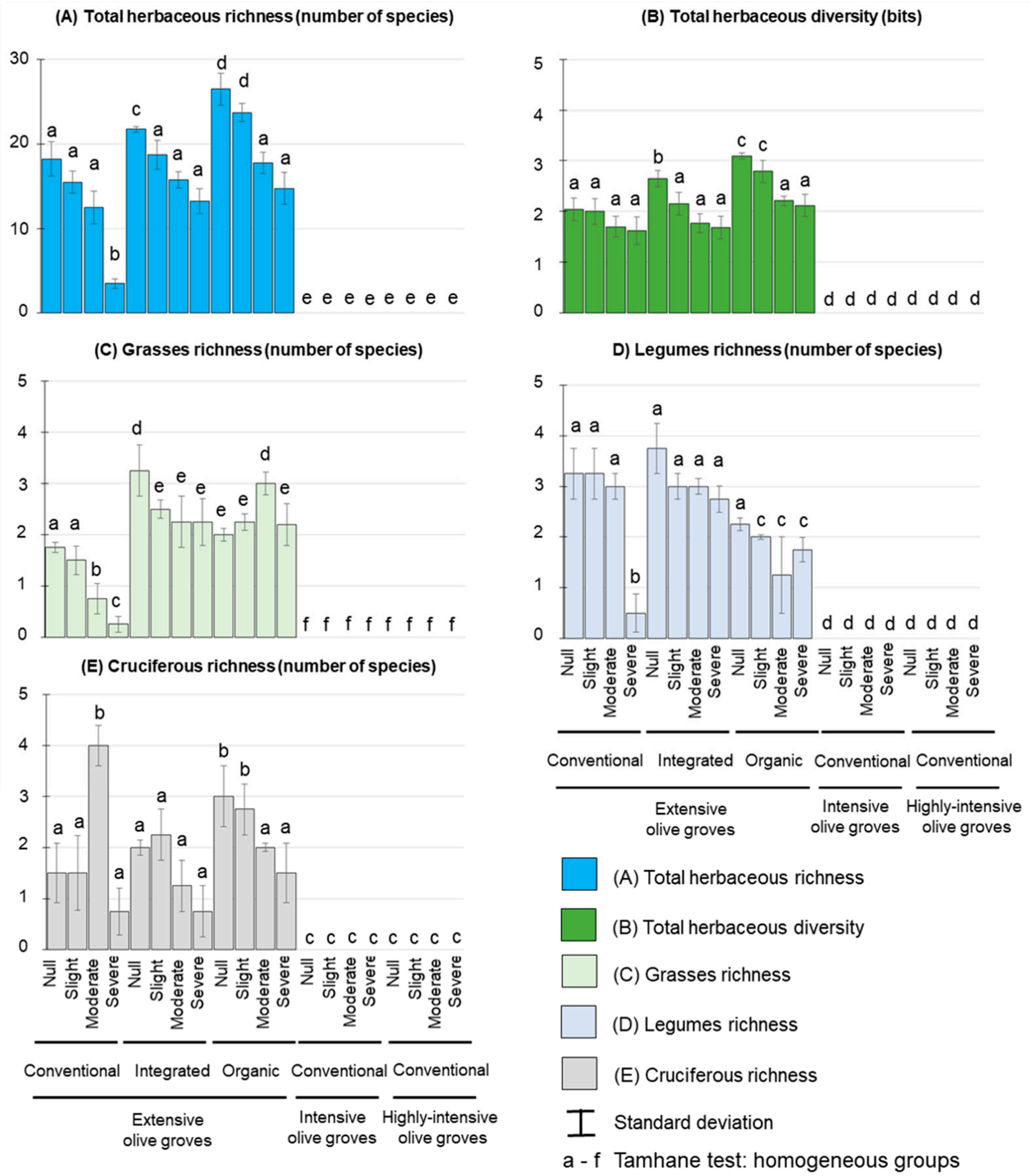


**Figure 6.** Mean values and standard deviations for total herbaceous richness (**A**, number of species) and diversity (**B**, bits) for each erosion level and type of olive grove. Additionally, mean values and standard deviations are also attached for the specific richness of grasses (**C**), legumes (**D**), and cruciferous (**E**). Indexes, a–f, indicate the clusters generated in the Tamhane post-hoc test to establish similar categories.

### *3.2. Impact of Chemical Fertilizers on the richness and Diversity of the Olive Grove*

Multiple regression models implemented to analyze the lepidopteran and vegetation species diversity and richness showed strong correlations with key soil parameters (Table 2). Consideration, in statistically significant cases, of the interactions between the independent variables (i.e., chemical fertilizers), did not increase the $R^2$ parameter, and thus the most robust regression models were obtained without the need to incorporate any mutual interactions into the model. The results showed $R^2$ percentages higher than 50% in all cases, consolidating explanatory models for more than half of the variability of the data. For all the dependent variables, the concentration of soil $NO_3{}^{2-}$, $PO_4{}^{-}$, and $K^+$ were negatively correlated with lepidopteran and herbaceous species richness and diversity. Herbaceous variables were strongly and negatively influenced by $K^+$, while lepidopteran richness and diversity were, respectively, negatively correlated with $NO_3^-$ and $PO_4^{3-}$. Finally, each herbaceous group was exclusively and negatively impacted by a specific soil nutrient; grasses by $K^+$, legumes by $NO_3^-$, and crucifers by $PO_4^{3-}$.

**Table 2.** Regression analysis results for each biological variable, specifying their units. The intercepts, along with the coefficients for each significant independent variable in the model including their units (in case of nonsignificant variables, no value is specified), and the $R^2$ values (%) are specified.

| Variable | Intercept | Nitrates (ppm) | Phosphates (ppm) | Potassium (mg kg$^{-1}$) | $R^2$ (%) |
|---|---|---|---|---|---|
| Lepidoptera richness (n° species) | 3.59 | — | −0.08 | −0.01 | 70.62 |
| Lepidoptera diversity (bits) | 10.91 | 0.32 | −0.22 | −0.07 | 78.72 |
| Herbaceous richness (n° species) | 36.39 | — | — | −0.21 | 83.96 |
| Herbaceous diversity (bits) | 3.47 | — | −0.10 | −0.11 | 92.29 |
| Grass richness (n° species) | 4.40 | — | — | −0.03 | 60.76 |
| Legume richness (n° species) | 3.38 | −0.25 | — | — | 55.44 |
| Cruciferous richness (n° species) | 2.42 | — | −0.18 | — | 50.38 |

## 4. Discussion

### *4.1. Relationships between Chemical Fertilizer Use, Soil Erosion and Agricultural Intensification*

Agricultural intensification is aimed at increasing crop production by adopting different management actions, such as increasing plant density, incorporating irrigation, and the addition of chemical fertilizers (mainly N, P, and K) [5,24,25,43]. In this sense, the addition of chemical fertilizers in conventional intensive (200–800 trees ha$^{-1}$) and highly intensive (800–2000 trees ha$^{-1}$) olive groves increases their productivity but results in environmental externalities that are directly linked to the use of these products [20,21]. The results obtained in the present study coincide with the trends observed by Proietti et al. [30] and Palma et al. [71], where it was shown that the addition of NPK fertilizers was maximized in intensive agricultural systems, leading to multiple environmental impacts, such as the loss of biodiversity and deterioration of bioindicators, damaging the environmental quality of agriculture at the plot, farm, and landscape scales.

Agricultural intensification aims to maintain stable production yields in soils, regardless of whether these degraded at multiple scales [53,72]. Laminar and rill hydric soil erosion is one of the main threats to the sustainability of olive groves in the Iberian Peninsula [12,18]. On the one hand, soil erosion drives multiple impacts over the economic profitability of crops, with studies estimating a loss of between 5–66 € ha$^{-1}$ year$^{-1}$ in typical agricultural systems in Spain (i.e., horticulture, olive groves, and cereal steppes) [73]. On the other hand, erosion processes contribute to the gradual loss of soil horizons and associated soil organic matter, thus resulting in the demand for a greater quantity of chemical fertilizers to maintain production [53,60,72]. The incorporation of these inputs is calculated based on the ratios between soil loss and yields in agriculture, a relationship that has been widely studied and takes the shape of a complex negative exponential model, where yield loss accelerates progressively over time due to the fertility soil loss [59,74].

Considering the impacts of erosion on soil fertility and the agricultural productive potential of land, along with the short-term productive objective of intensive and highly intensive agriculture [20,59,74], our research showed a higher concentration of $NO_3^-$, $PO_4^{3-}$, and $K^+$ in plots with higher olive tree densities and also in plots with higher rates of soil erosion, reaching levels that can trigger diffuse, terrestrial, and atmospheric pollution phenomena due to surface- and groundwater runoff [57,71,72]. On the other hand, $K^+$ is a cation that is asymptotically related to agricultural production up to values of 170 mg kg$^{-1}$, and its uptake by the olive tree is limited in calcareous soils that are partly present in Alentejo, and therefore are more highly in demand in those farms where olive productivity decreases due to soil degradation driven by erosion [18,59].

Our results showed a higher risk of diffuse pollution and environmental impacts of NPK excesses in the conventionally managed highly eroded intensive and highly intensive olive orchards when compared to extensive and conventional, integrated, or organic olive groves. Future studies should complement these results by considering other soil parameters related to agricultural production, including also microelements (e.g., magnesium (Mg) or calcium (Ca), among other minor ions such as zinc (Zn), sodium (Na), or chlorine ($Cl^-$)) that may impact olive tree production and soil ecosystem services [75,76]. In this study, olive tree density was assessed only for certain management systems (conventional), missing, for example, the assessment of organic intensive and highly intensive olive groves, which are still very scattered in the region, and yet they are gradually increasing [25,36,37]. This oversimplification of the heterogeneous reality in Alentejo, where multiple combinations between planting densities and olive grove management systems are in place, will need to be resolved in the near future. This will be an important asset to evaluate how the combination of certain multifunctional management approaches (i.e., integrated and organic), agricultural practices (e.g., the implementation of a plant cover that mitigates the erosive effects, or reduction in tillage), and the efficient use of machinery (i.e., technification of agriculture towards 2.0 or 4.0 management systems) result in novel and sustainable farming systems that harmonize the productive (i.e., securing a farm income that allows a fair standard of living for farmers) and environmental dimensions (i.e., minimization of impacts derived from agriculture on environmental quality at plot, farm, and landscape scales), thereby responding to key societal demands for agriculture [27,44,77,78].

### *4.2. Impact of Chemical Fertilizers on Fauna and Flora in Olive Groves*

Olive groves generally stand out as potential reservoirs of a wide agrobiodiversity of both fauna (e.g., predominantly specific groups of invertebrates such as insects or insectivorous and wintering birds) and flora [3,9,10], acting as a source of supporting ES that themselves act as a basis for other provisioning, regulating, and cultural ES [13–15,36]. Although the agrobiodiversity standards of olive groves can potentially be very high, there are only a few specific plants and animals that act as bioindicators of environmental quality (e.g., ant-like hymenopterans, detritivorous and decomposing coleopteran or beetles, and lepidoptera or butterflies) [5,18,20,21]. These organisms are very sensitive to any environmental disturbance resulting from agricultural intensification, such as the increased application of chemical compounds to crops. On the other hand, herbaceous vegetation usually stands out as an indicator of the ecological status of the olive groves. Unfortunately, herbaceous vegetation in olive groves is not properly valued by too many landowners and land managers. Herbaceous vegetation is often removed from conventional olive groves via chemical herbicides or plowing. The argued reasons are to avoid any interspecific competition with the olive tree in terms of water and nutrient absorption, as well as to facilitate the use of machinery for harvesting the olives [79,80]. However, maintaining adequate plant cover in olive groves bears multiple potential benefits without affecting nutrient uptake by olive trees, including the mitigation of soil erosion and loss through the increased stabilization of soil horizons and increased retention of organic matter in the soils [22,26,81], as well as contributing to the generation of heterogeneous landscapes which, in turn, constitute refuges essential for agricultural animal biodiversity [82].

The results obtained by our analysis of the richness and diversity of diurnal lepidoptera confirm those of Scandurra et al. [83], reinforcing the negative influence of the addition of NPK fertilizers on biodiversity. In this sense, the lepidoptera richness and diversity in the olive groves sampled in Alentejo decreased in crops with higher erosion rates and tree density (i.e., conventionally managed intensive and highly intensive olive groves). In these plots, NPK fertilizers were added to maintain stable crop production [59,72–74]. The lepidoptera richness and diversity results standout as important environmental bioindicators of fauna in olive groves, especially considering the high sensitivity of these organisms to tillage practices and diffuse, terrestrial, and atmospheric pollution [83,84]. Future studies should expand on the analysis of other soil fauna bio-indicators in order to detect consistencies and inconsistencies amongst the trends already unveiled. Agricultural intensification is acknowledged to enhance spatial homogeneity and territorial simplification, which considerably reduces the presence of butterflies in crops [20,21]. In our study, $PO_4^{3-}$ and $K^+$ negatively affected the richness and diversity of lepidoptera in Alentejo. This is contrary to the results obtained by Nilsson et al. [85] in Southern Sweden, who conversely revealed a positive influence of soil $NO_3^-$ content on the diversity of these organisms. However, this result should not be interpreted as categorical, as it was probably influenced by the fact that the higher N content of soils favors the development of a spontaneous plant cover with a predominance of nitrophilous species such as *Festuca indigesta* (Boiss., 1838) or *Vicia sativa* (L., 1753), generating suitable habitats for this type of fauna [5,82].

In addition, it also became evident that the implementation of partial or total herbaceous cover as an erosion mitigation measure was more efficient in extensive olive groves under integrated (where the application of NPK fertilizers is regulated by technical control agencies) and organic management systems, being lower in intensive and highly intensive olive groves. This allows us to predict a greater loss of soil horizons and nutrients in intensive than in extensive olive farms [7,25]. Both in Spain and Portugal, the implementation of a (largely herbaceous) plant cover is mandatory in integrated and organic management systems, which can be set in the form of living (spontaneous or sown) or inert covers (e.g., pruning waste) [4,5,24,43]. In this sense, the implementation of participatory seminars and workshops with social actors should be carried out to raise awareness and coconstruct new evidence on the benefits of these practices in intensive and highly intensive agricultural systems. Importantly, this is a measure increasingly common in olive farms with high plant densities in Alentejo, which are increasingly acknowledging the importance of maintaining multifunctionality and minimizing the negative externalities of agricultural intensification [76–78]. When analyzing the specific impacts of NPK fertilizers on plant richness and diversity, an inverse relationship was observed between the concentration of chemical inputs and the presence of herbaceous plants, with $NO_3{}^{2-}$, $PO_4{}^{-}$, and $K^+$ acting as herbicides and soil pollution agents [22,31,57], in alignment with the results by Palma et al. [71].

Finally, it is worth mentioning that plant cover crops sown in olive groves tend to be dominated by grasses and crucifers because their biomass helps to minimize the effects of soil erosion as they have a root system that promotes the production of soil aggregates, thus preventing the soil compaction caused by tillage practices [62,86]. In addition, legumes that help to fix nitrogen and increase soil fertility in crops [87] are equally common. In our plots, $K^+$ specifically impacted, negatively, the development of grasses, a plant family dominated by nitrophilous species [88], while $NO_3^-$ and $PO_4^{3-}$ impacted the development of legumes and crucifers, respectively, due to their vulnerability to pollution processes, sustained by their low tolerance degrees to the presence of the types of chemical compounds most frequently dissolved in irrigation water or groundwater [22,81]. In view of the need to tackle soil erosion in olive groves and thus increase their long-term sustainability standards, and to ensure a stable supply of multiple ES, it is essential to control NPK fertilizer concentrations on farms. To meet this end, the combination and rotation of different grass species should be encouraged. This implementation should be grounded on a more cohesive, coordinated, and effective framework of regional, national, and European land-use policies, along with an active involvement of farmers and associations, in the implementation of the Common Agricultural Policy (CAP). This is essential for the enhancement of the values of nonproductive ecosystem services potentially delivered by olive groves [19,89].

## 5. Conclusions

Through our research, we could verify the impact of management systems and erosion rates on the concentration of agrochemical inputs in olive groves of the Portuguese region of Alentejo. In conventionally managed intensive and highly intensive groves, a greater amount of NPK fertilizers is applied, minimizing plant cover and thus negatively impacting floral and faunal biodiversity. Ultimately, this led to a higher risk of diffuse pollution at plot and landscape scales. Extensive conventionally managed olive groves showed intermediate concentrations of fertilizers, whilst in integrated olive groves and, more significantly, in organic ones, the use of these compounds was minimized, thus promoting the ecological integrity of landscapes, which contained higher levels of richness and diversity of herbaceous and lepidopteran bio-organisms. On the other hand, soil erosion was confirmed to be directly related to the use of chemical fertilizers, with a greater addition of these inputs coinciding with plots of greater erosion rates. This demands more innovative management models that prevent soil degradation from negatively impacting crop productivity.

Considering the relevance of the olive sector in Portugal, and the fact that agricultural technification and intensification is increasingly being promoted, our results can inform decision making by multiple social actors, on which management systems could be implemented to promote greater multifunctionality and biodiversity standards for the territories. Future studies should consider a greater diversity of bioindicators, with special attention to assess the empirical consequences of the implementation of sustainable soil management practices (i.e., plant cover, minimum tillage) in crops with high plant densities, thus potentially contributing to moving the sustainable agricultural intensification of olive groves from theory to practice.

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land11122194/s1: the data presented in this study are available in the electronic supplementary material attached (Online Resources 1–5).

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