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Variability of Grassland Soils' Properties in Comparison to Soils of Other Ecosystems

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Abstract: The variety of natural conditions and land use patterns determine high variability of soil properties. This study focused on the analysis of chemical, physical, and biological properties of grassland (GL) soils (situated on slopes—GLS, and on alluvial plains—GLP) in comparison with soils of other ecosystems (arable land, forest land, riparian zone) in Central Slovakia. We applied an indicator's method combined with models of these properties. The studies showed a large variability, more pronounced in GLS than in GLP. GLP soils were characterized by the highest number, biomass, and diversity of earthworms among all ecosystems. GL soils, in addition to FL soils, also have a relatively high capacity for water retention and C and N storage. However, we found an unfavorable state in available phosphorus, with GLS showing the lowest levels among compared ecosystems.

Keywords: grassland soil; available nutrient; earthworm community; soil water retention; carbon and nitrogen stock

1. Introduction

Grasslands cover about 40% of the Earth's surface, comprising open grassland, grassy shrublands, and savannas, and almost 70% of agricultural lands [1,2]. In the EU, grasslands cover 34% of the land territory [3] and are very diverse, resulting from inherent factors such as climate, soil, and management intensities [4]. They occur commonly where site-specific conditions are less favorable for crop farming [5].

Different types of grasslands exhibit obvious differences in their properties and ecosystem functions, which is also reflected in the fulfilment of their ecosystem services. Therefore, it is of great significance to investigate them [6]. The most important characteristics of grassland soils are their dark, organic matter-rich surface layers and their substantial contents of nutritive elements [7].

Grasslands provide many benefits to humankind including all four categories of ecosystem services, provisioning, regulating, supporting, and cultural [8,9]. They provide feed for livestock, food for people through livestock and its products as meat, milk, and fibre [10]. Grasslands significantly contribute to the regulation of the water cycle [11], nutrient cycle [12], carbon sequestration [13], nitrogen storage [14], or erosion control [15]. Grasslands also play a key role in maintaining biodiversity [16] and provide a buffer against climate variability [17].

Provisioning ecosystem services are particularly emphasized, also having market value (as fodder and livestock production) [18]. Other regulating, supporting, and cultural

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services with indirect (such as water and climate regulation) or intangible effect (such as cultural services) are often ignored in land management [19].

It should be emphasized that soil ecosystem services depend on soil properties and their interactions. The definition of the so-called soil-related ecosystem services refers to the frameworks by Dominati et al. [20] and Adhikari and Hartemink [21], emphasizing the link between soil properties and related ecosystem services. However, many studies on the valuation of ecosystem services lack a soil component or soil is poorly defined or too generalized [22]. But soil properties are directly linked to soil functions that ultimately determine the delivery of ecosystem services, which is well documented in many studies [23–25]. For example, the filtration of water is regulated by soil properties such as pore size or bulk density, while the biomass production is determined by nutrient availability or soil moisture.

Similarly, the spatial aspects and dynamics of soil properties to ecosystem services have been studied through mapping or modeling without terrain research as representative, as it is a time- and resource-demanding process. Proxy data are often used, as they are useful in regions where data are scarce [26]. However, due to the possible high spatial variability of soil properties, these models may be questioned. Hence, the results that are the outputs of detailed field research gain importance here.

Despite the importance of grassland, over the past century, changes in land use have led to extensive loss of temperate semi-natural grasslands [27], conversion into agricultural areas, abandonment, or afforestation [28]. Furthermore, high conservation alluvial grasslands historically shaped by river dynamics [29] have seen decline due to river regulations and agricultural intensification [30].

Grassland degradation is widespread and accelerating in many parts of the world, with up to 49% of global grasslands having been degraded to some extent [31]. Grassland degradation thus creates major environmental problems, as grasslands play a critical role in ecosystem services [32].

For effective land management, it is necessary to know and analyze the diverse soils of grasslands, also in comparison with the soils of other ecosystems, and to determine the positive aspects but also the possible negative ones associated with their management. Here, we sampled and measured soil properties and tested the hypothesis that grassland soils are characterized by high diversity conditioned by various factors (e.g., soil type, landscape unit). Our goal was to cover a broad range of soil properties including chemical, physical, and biological. Thus, the main objectives of this study were (1) to characterize different soil types of grasslands developed under different climatic and natural conditions (roughly divided into two groups: slope and plain grasslands) also in comparison to the soils of other different ecosystems (arable land, forest land, riparian zone) by basic chemical, biological, and physical properties, (2) to identify critical properties of grassland soils based on the assessment, (3) to analyze mutual relationships between soil properties, and (4) to examine how land use influences soil properties.

2. Materials and Methods

2.1. Site Description

This study was conducted in Central Slovakia, as a part of the Central and Inner Western Carpathians. The region has a diverse topography that ranges from mountains primarily in the north to rolling hills in the central part, and basins in the south. The elevation varies greatly, with many different landscapes. The climate is temperate but is influenced by elevation and relief. The region is dominated by forests followed by grasslands and arable land [33]. Permanent grasslands are considered the most important semi-natural habitat in the region for the provision of ecosystem services and for the maintenance of biodiversity.

2.2. Sampling Design

Twenty study sites were selected with 20 permanent grasslands, of which 11 on mountain slopes (slope grasslands—GLSs) and 9 on river alluvial plains (plain grasslands—GLPs), together marked as GLSP. They were situated between 155 m and 930 m of altitude. All 9 GLPs were developed on Fluvisols, and GLSs were developed on 3 different soil types, Cambisols (8), Leptososls (2), Planosol (1), classified according to the World Reference Base for Soil Resources [34]. In order to compare grassland soils with soils of other ecosystems, we selected 18 additional localities within study sites. Within 6 study sites in the plains, we selected a riparian zone in addition to a grassland and within 6 study sites with sloping land, in addition to a grassland, a location with arable land and one with forest land. Thus, at 20 study sites, we selected 38 localities in total, of which 20 were grasslands (11 GLSs and 9 GLPs), 6 arable lands (ALs), 6 forest lands (FLs), and 6 riparian zones (RZs) (Figure 1, Table 1). Grasslands were grazed or mowed. Arable lands were managed intensively, less intensively, or ecologically. Forests were deciduous, mixed, and coniferous. The riparian vegetation consisted mainly of trees such as willows, poplars, shrubs, grasses, and herbs.

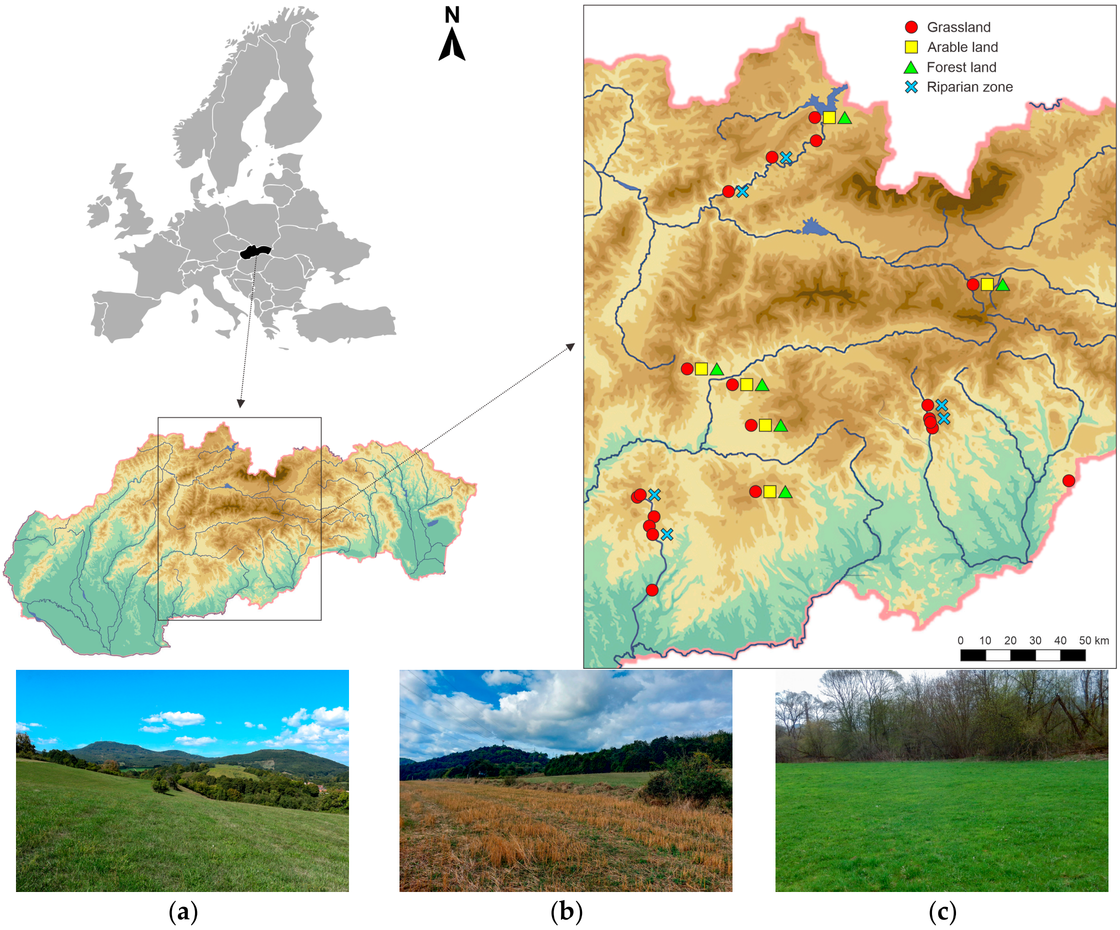


Figure 1. Map of localities in Central Slovakia and photos from selected study sites; (**a**) Grassland on slope; (**b**) Arable land, grassland, and forest land on slope; (**c**) Grassland and riparian zone on plain.

Table 1. Characteristics of the localities.

Cadastre	Locality	Latitude (N)	Longitude (E)	Altitude (A) (m)	Soil Type	Land Use	Landscape Unit
Liptovska Teplicka	GL_S_LP_LT	N48°57.011	E20°06.875	930	LP	GL	S
Stara Huta	GL_S_CM_SH	N48°27.880	E19°17.490	783	CM	GL	S
Banska Stiavnica	GL_S_CM_BS	N48°26.749	E18°53.297	659	CM	GL	S
Oravska Jasenica	GL_S_CM_OJ	N49°24.106	E19°25.976	656	CM	GL	S
Stiavnicke Bane	GL_P_FL_SB	N48°26.136	E18°52.632	648	FL	GL	P
Tajov	GL_S_CM_TA	N48°44.837	E19°03.153	597	CM	GL	S
Nizna	GL_S_CM_NI	N49°18.261	E19°31.029	572	CM	GL	S
Dolna Lehota	GL_S_FL_DL	N49°15.947	E19°21.743	508	FL	GL	P
Horna Micina	GL_S_CM_HM	N48°42.363	E19°13.330	462	LP	GL	S
Zaskov	GL_S_FL_ZA	N49°11.343	E19°12.488	451	FL	GL	P
Ocova	GL_S_PL_OC	N48°36.390	E19°17.122	412	PL	GL	S
Tisovec	GL_P_FL_TI	N48°39.710	E19°56.470	385	FL	GL	P
Svaty Anton	GL_P_FL_SA	N48°22.979	E18°55.854	353	FL	GL	P
Hacava	GL_P_FL_HA	N48°37.257	E19°57.056	351	FL	GL	P
Kecovo	GL_S_CM_KE	N48°28.586	E20°27.858	344	CM	GL	S
Prencov	GL_S_CM_PR	N48°21.675	E18°55.174	335	CM	GL	S
Hnusta	GL_S_CM_HN	N48°36.012	E19°57.588	328	CM	GL	S
Hnusta	GL_P_FL_HN	N48°36.900	E19°57.440	322	FL	GL	P
Prencov	GL_P_FL_PR	N48°20.859	E18°55.871	288	FL	GL	P
Dvorniky	GL_P_FL_DV	N48°12.168	E18°55.733	155	FL	GL	P
Liptovska Teplicka	AL_S_LP_LT	N48°57.009	E20°06.749	920	LP	AL	S
Stara Huta	AL_S_CM_SH	N49°27.897	E19°17.500	781	CM	AL	S
Oravska Jasenica	AL_S_CM_OJ	N49°24.117	E19°25.982	656	CM	AL	S
Tajov	AL_S_CM_TA	N48°44.847	E19°03.117	595	CM	AL	S
Horna Micina	AL_S_LP_HM	N48°42.326	E19°13.320	460	LP	AL	S
Ocova	AL_S_PL_OC	N48°36.383	E19°17.169	410	PL	AL	S
Liptovska Teplicka	FL_S_FL_LT	N48°56.828	E20°06.483	925	LP	FL	S
Stara Huta	FL_S_CM_SH	N49°27.833	E19°17.472	777	CM	FL	S
Oravska Jasenica	FL_S_CM_OJ	N49°24.180	E19°25.737	667	CM	FL	S
Tajov	FL_S_CM_TA	N48°44.791	E19°03.119	580	CM	FL	S
Horna Micina	FL_S_LP_HM	N48°42.385	E19°13.378	465	LP	FL	S
Ocova	FL_S_PL_OC	N48°36.489	E19°17.001	437	PL	FL	S
Stiavnicke Bane	RZ_P_FL_SB	N48°26.113	E18°52.635	648	FL	RZ	P
Dolna Lehota	RZ_P_FL_DL	N49°15.935	E19°21.757	505	FL	RZ	P
Zaskov	RZ_P_FL_ZA	N49°11.367	E19°12.420	451	FL	RZ	P
Tisovec	RZ_P_FL_TI	N48°39.704	E19°56.472	385	FL	RZ	P
Hnusta	RZ_P_FL_HN	N48°36.891	E19°57.465	322	FL	RZ	P
Prencov	RZ_P_FL_PR	N48°20.866	E18°55.900	284	FL	RZ	P

Abbreviations: CM—Cambisol, LP—Leptosol, FL—Fluvisol, PL—Planosol, GL—Grassland, AL—Arable land, FL—Forest land, RZ—Riparian zone, S—Slope, P—Plain.

2.3. Soil Chemical, Physical, and Biological Analysis

At each locality, five sampling points with a Z-shaped pattern were selected. Soil samples were collected at 0–20 cm during spring (March–May) or autumn (September–October) from 2019 to 2023. Field samples consisted of approximately 1 kg of soil; they were mixed, homogenized, air-dried, and sifted through a 2 mm mesh sieve. Soil reaction (pH/H_2O) was measured with a potentiometer in a 1:1 soil-to-water mix, and exchangeable soil reaction (pH/KCl) was determined by the KCl method as a 1:2.5 soil:1M KCl solution mix. Soil organic carbon (SOC) content was determined using an oxidimetric method according to Tjurin (a modification of Nikitin) [35]. Organic matter content (OM) was recalculated from SOC using 1.724 coefficient. Total nitrogen content (NT) was determined by the Kjeldahl method [36]. The available nutrients P, K, and Mg were extracted by Melich III [37]. P was determined calorimetrically on the analyzer Scalar, Mg and K by flame photometry. The carbon and nitrogen stock were calculated for a 20 cm thick upper soil layer according to Tan [38] and Chen [39] (Equation (1)):

$$CS = \sum_{i=1}^{n} SOCi * BDi * Hi * \left(1 - \frac{G}{100}\right) * 10^{-1} \tag{1}$$

where *CS* is the C stock pool (t.ha^{-1}) of the evaluated soil profile, *SOCi* is SOC content (g.kg^{-1}), *BDi* is the bulk density (g.cm^{-3}), *Hi* is the soil thickness (cm), and *G* is the volume percent of gravel and stones (particle size > 2 mm) in layer i, respectively.

A similar approach was used to calculate NS (t.ha^{-1}) (Equation (2)):

$$NS = \sum_{i=1}^{n} SNTi * BDi * Hi * \left(1 - \frac{G}{100}\right) * 10^{-1} \tag{2}$$

where *NS* is the N stock pool (t.ha^{-1}) of the evaluated soil profile, *SNTi* is the total soil nitrogen content (g.kg^{-1}), *BDi* is the bulk density (g.cm^{-3}), *Hi* is the soil thickness (cm), and *G* is the volume percent of gravel and stones (particle size > 2 mm) in layer i, respectively.

Particle size fractions (clay, silt, sand, and gravel) were determined by the pipette method using soil particle sedimentation and classified according to the United States Department of Agriculture system. Bulk density (BD) was determined using undisturbed soil samples that were hermetically sealed in stainless steel tubes and taken to the laboratory for analyses using the gravimetric method according to Novák [40]. Particle density (PD) was measured by the pycnometer method according to Blake and Hartage [41]. The hydrological soil properties as indicators were calculated according to Gupta and Larson [42] for temperate pedotransfer functions [43] as field water capacity (FWC) (Equation (3)), wilting point (WP) (Equation (4)), available water capacity (AWC) (Equation (5)), and soil water deficit index (SWDI) (Equation (6)):

$$\begin{aligned} FWC = 0.003075 * Sa + 0.005886 * Si + 0.008039 * Cl + 0.002208 * SOM \\ -0.01434 * BD \end{aligned} \tag{3}$$

$$\begin{aligned} WP = -0.000059 * Sa + 0.001142 * Si + 0.005766 * Cl + 0.002228 * SOM \\ +0.002671 * BD \end{aligned} \tag{4}$$

where *Sa* is the percentage of sand, *Si* is the percentage of silt particles, *Cl* is the percentage of clay particles, *SOM* is the percentage of soil organic matter, and *BD* is the bulk density.

$$AWC = FWC - WP\ (\%) \tag{5}$$

where *FWC* is the field water capacity in %, *WP* is the wilting point in %.

The SWDI proposed by Martinez-Fernandez et al. [44] characterizes drought based on soil moisture and calculated hydrological soil properties. This index is capable of adequately identifying the main attributes that define a drought event. For the calculation, the following formula was used:

$$SWDI = \left(\frac{SMa - FWC}{AWC}\right) * 10 \tag{6}$$

where *SMa* is the actual soil moisture in %, *FWC* is the field water capacity in %, and *AWC* is the available water capacity in %.

SWDI positive values mean an excess of water in the soil. When SWDI equals zero, soil is in the field capacity of the water content (that is, without water deficit). Negative values indicate soil drought. The SWDI in the range 0–-2 means mild, -2–-5 moderate, -5–-10 severe, and ≤ -10 extreme drought level.

Various chemical, physical, and biological properties were measured directly on the ground at the points from which the samples were collected for chemical and physical analyses. Earthworms were sampled in five 30 cm × 30 cm × 20 cm soil monoliths. The excavated soil monoliths were broken by hand, all earthworms collected, washed, counted, weighed, and thereafter identified to species level [45,46]. Earthworm community was assessed by earthworm number (EN), biomass (EB), and diversity (as Shannon's diversity index H).

Redox potential (Eh) was measured by the Oxygen Diffusion meter (Eijkelkamp Equipment for Soil Research, The Netherlands). Penetrometric resistance (PR in MPa.cm^{-1}) with related depth (DPR in cm) was measured by a penetrologger (Eijkelkamp Equipment for Soil Research, The Netherlands). Actual soil moisture (SM in %) and soil temperature (ST in °C) were measured using a WET sensor (Delta-T Devices Ltd. Cambridge, UK). Soil respiration rates as the net carbon exchange rate (NCER in $\mu\text{mol CO}_2.\text{m}^{-2}\text{s}^{-1}$) were measured by the closed-chamber method using an infrared gas analyzer (LC-Pro+, ADC BioScientific Ltd., Hoddesdon, UK).

2.4. Data Analysis

Data were subjected to descriptive statistics such as the mean, Spearman's correlation coefficient, analysis of variance (ANOVA), and hierarchical cluster analysis (HCA). The Shapiro–Wilk test was used to determine whether data come from a normal distribution. Levene's test was used to assess the equality of variances. The Tukey HSD test was used as a post hoc test. Because some data follow non-normal distribution, we used Spearman's correlation coefficient to verify correlation between all variables considering all study sites (n = 38). Subsequently, based on the normality and homogeneity tests, we selected variables tested by ANOVA and HCA considering 30 study sites (n = 30 of 6 GLSs, 6 FLs, 6 ALs, 6 RZs, 6 GLPs). The data were analyzed by using SPSS Statistics 28.

3. Results

3.1. Soil Chemical, Physical, and Biological Properties in Different Ecosystems

The basic statistical characteristics of the chemical, biological, and physical soil properties in GL, AL, FL, and RZ are reported in Tables 2–4.

In the GL soil group, most soil characteristics showed a large variability of selected soil properties, e.g., $\text{pH/H}_2\text{O}$ ranges from 4.83 to 9.01. Higher variability was more pronounced in GLS compared to GLP soils. When comparing specific properties, the average values of pH and Eh were higher in GLP soils, and on the other hand, properties such as SOC or NT were lower corresponding to a lower supply of organic matter. In addition, the organic matter in GLP soils was of poorer quality, expressed by a higher C/N ratio. In GLSP soils, available Mg (ranging from 220.1 to 4700.4 mg.kg^{-1}) was at a very high level, available K (ranging from 49.1 to 349.3 mg.kg^{-1}) at high level, and available P (ranging from 0.5 to 33.7 mg.kg^{-1}) at a very low level. In GLS soils, Mg reserves were slightly higher, and K and P reserves were found to be lower than those found in GLP soils. Among other ecosystems, GLSP soils were characterized by lower contents of available K and conversely, GLS soils had the highest Mg reserves. Available P reserves in GL and FL soils were the lowest.

Table 2. Soil chemical properties.

Eco-system	Statistical Characteristics	pH/H_2O	pH/KCl	Eh (mV)	SOC ($g\ kg^{-1}$)	SOM ($g\ kg^{-1}$)	NT ($g\ kg^{-1}$)	C/N	P ($mg\ kg^{-1}$)	K ($mg\ kg^{-1}$)	Mg ($mg\ kg^{-1}$)
GLSP	$\bar{x}$ ± SD	6.37 ± 1.03	5.93 ± 1.17	364 ± 47	28.55 ± 11.64	49.22 ± 20.06	2.70 ± 1.22	10.94 ± 2.98	8.07 ± 9.17	187.8 ± 93.2	818.9 ± 1017.55
	Min	4.84	3.98	291	13.88	23.93	1.42	7.24	0.04	49.1	220.14
	Max	9.01	8.93	451	51.81	89.32	6.09	20.93	33.73	349.3	4700.38
GLS	$\bar{x}$ ± SD	6.20 ± 1.23	5.84 ± 1.43	361 ± 52	33.74 ± 12.73	58.17 ± 21.95	3.27 ± 1.37	10.78 ± 3.47	5.43 ± 6.36	188.50 ± 94.63	1083.24 ± 1286.40
	Min	4.84	3.98	291	15.00	25.86	1.42	7.24	0.04	71.69	220.14
	Max	9.01	8.93	451	51.81	89.32	6.09	20.93	22.83	349.30	4700.38
GLP	$\bar{x}$ ± SD	6.57 ± 0.63	6.06 ± 0.70	368 ± 36	22.21 ± 5.16	38.28 ± 8.89	2.02 ± 0.40	11.15 ± 2.10	11.30 ± 10.33	187.01 ± 86.64	495.90 ± 282.37
	Min	5.36	5.08	317	13.88	23.93	1.42	7.27	2.87	49.11	238.08
	Max	7.44	7.19	448	31.48	54.27	2.72	13.94	33.73	319.35	1078.60
AL	$\bar{x}$ ± SD	6.33 ± 0.59	5.59 ± 0.65	349 ± 29	25.21 ± 14.62	43.96 ± 26.19	2.31 ± 0.94	10.25 ± 1.62	28.45 ± 7.97	409.90 ± 472.49	513.40 ± 270.32
	Min	5.34	4.84	289	10.50	18.10	1.23	8.54	13.88	126.66	127.36
	Max	7.15	6.70	379	53.63	95.46	3.99	13.44	38.23	1461.37	949.12
FL	$\bar{x}$ ± SD	5.88 ± 0.71	5.02 ± 1.11	381 ± 66	74.43 ± 39.18	128.31 ± 67.55	4.62 ± 1.41	15.40 ± 4.32	5.73 ± 4.96	252.97 ± 126.37	640.13 ± 332.46
	Min	5.16	3.84	247	30.00	51.72	3.16	7.13	0.04	106.79	283.41
	Max	7.25	7.12	443	145.44	250.74	7.38	19.71	13.49	437.73	1273.57
RZ	$\bar{x}$ ± SD	7.22 ± 0.46	6.69 ± 0.67	448 ± 220	27.38 ± 3.21	47.19 ± 5.53	2.40 ± 0.53	11.82 ± 2.17	17.58 ± 13.96	244.53 ± 123.54	645.06 ± 351.06
	Min	6.26	5.30	300	23.76	40.96	1.66	8.62	4.63	97.70	266.36
	Max	7.65	7.20	935	33.45	57.67	3.34	14.31	46.67	420.92	1164.62

Abbreviations: GLSP—Grasslands on slope and plain, GLS—Grassland on slope, GLP—Grassland on plain, AL—Arable land, FL—Forest land, RZ—Riparian zone, pH—Soil reaction, Eh—Redox potential, SOC—Soil organic carbon, SOM—Soil organic matter, NT—Nitrogen total, C/N—Carbon to Nitrogen ratio, P—Available P, K—Available K, Mg—Available Mg.

Table 3. Soil physical properties.

Eco-system	Statistical Characteristics	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	BD (g cm^{-3})	PD (g cm^{-3})	ST (°C)	SM (%)	PR (MPa. cm^{-1})	DPR (cm)
GLSP	$\bar{x} \pm$ SD	12.2 ± 7.8	46.2 ± 14.7	41.5 ± 16.2	9.3 ± 11.5	1.23 ± 0.13	2.34 ± 0.14	15.1 ± 6.9	26.7 ± 9.2	1.2 ± 0.2	23.1 ± 16.6
	Min	5.3	22.7	12.2	1.1	0.95	2.06	4.3	12.9	0.8	4.4
	Max	38.3	76.0	70.4	50.0	1.47	2.61	28.3	47.6	1.7	62.0
GLS	$\bar{x} \pm$ SD	14.4 ± 9.6	50.8 ± 15.6	34.7 ± 15.9	11.1 ± 13.9	1.24 ± 0.12	2.33 ± 0.15	14.2 ± 7.1	25.7 ± 9.1	1.2 ± 0.2	26.5 ± 18.9
	Min	5.3	24.1	12.2	1.1	1.05	2.06	4.3	12.9	0.8	4.4
	Max	38.3	76.0	68.6	50.0	1.43	2.56	24.2	40.4	1.7	62.0
GLP	$\bar{x} \pm$ SD	9.5 ± 2.8	40.7 ± 10.6	49.8 ± 11.6	7.0 ± 6.7	1.22 ± 0.13	2.34 ± 0.12	16.1 ± 6.2	27.8 ± 8.7	1.1 ± 0.2	18.9 ± 11.2
	Min	6.3	22.7	33.0	2.0	0.95	2.16	7.4	16.6	0.8	7.4
	Max	15.2	57.9	70.4	20.0	1.47	2.61	28.3	47.6	1.6	38.3
AL	$\bar{x} \pm$ SD	14.8 ± 5.8	48.9 ± 10.8	36.4 ± 15.9	5.6 ± 5.3	1.21 ± 0.14	2.48 ± 0.16	17.3 ± 9.0	15.7 ± 6.1	0.9 ± 0.2	31.5 ± 25.2
	Min	8.2	36.1	13.1	0.0	0.97	2.24	4.6	6.1	0.5	6.8
	Max	25.2	67.5	55.8	15.0	1.39	2.68	26.5	22.7	1.2	72.9
FL	$\bar{x} \pm$ SD	15.5 ± 10.1	55.7 ± 6.7	28.8 ± 11.6	25.3 ± 16.7	0.98 ± 0.30	2.10 ± 0.29	13.3 ± 6.8	20.8 ± 10.0	1.1 ± 0.4	15.1 ± 7.0
	Min	9.3	48.1	9.2	1.5	0.46	1.58	3.5	7.9	0.5	5.7
	Max	38.0	68.5	41.2	50.0	1.46	2.50	20.9	34.9	1.4	27.4
RZ	$\bar{x} \pm$ SD	7.8 ± 1.9	37.3 ± 10.0	54.9 ± 11.0	15.0 ± 9.1	1.07 ± 0.14	2.38 ± 0.13	14.8 ± 4.8	21.7 ± 4.4	0.9 ± 0.3	35.2 ± 26.6
	Min	5.5	16.5	46.8	5.0	0.92	2.18	6.7	16.0	0.4	5.4
	Max	11.3	47.0	78.0	30.0	1.31	2.59	21.8	30.3	1.2	76.8

Abbreviations: GLSP—Grasslands on slope and plain, GLS—Grassland on slope, GLP—Grassland on plain, AL—Arable land, FL—Forest land, RZ—Riparian zone, BD—Bulk density, PD—Particle density, ST—Soil temperature, SM—Soil moisture, PR—Penetrometric resistance, DPR—Depth of penetrometric resistance measurement.

Table 4. Soil biological properties.

Eco-system	Statistical Characteristics	EN (ind.m^{-2})	EB (g.m^{-2})	H	NCER (µmol CO$_2$.m^{-2}s^{-1})
GLSP	$\bar{x} \pm$ SD	150.18 ± 132.28	50.81 ± 52.66	0.60 ± 0.45	2.26 ± 1.30
	Min	0.00	0.00	0.00	0.24
	Max	438.40	211.80	1.28	5.26
GLS	$\bar{x} \pm$ SD	87.58 ± 84.64	28.05 ± 22.85	0.36 ± 0.46	2.15 ± 1.22
	Min	0.00	0.00	0.00	0.45
	Max	307.20	67.80	1.28	5.26
GLP	$\bar{x} \pm$ SD	222.68 ± 132.43	78.62 ± 60.87	0.88 ± 0.20	2.40 ± 1.31
	Min	19.60	7.20	0.56	0.24
	Max	438.40	211.80	1.16	4.45
AL	$\bar{x} \pm$ SD	49.63 ± 71.73	17.39 ± 24.32	0.42 ± 0.45	0.93 ± 0.72
	Min	0.00	0.00	0.00	0.18
	Max	204.80	67.50	1.06	2.36
FL	$\bar{x} \pm$ SD	22.33 ± 15.23	6.48 ± 4.46	0.49 ± 0.53	2.44 ± 0.81
	Min	3.30	0.70	0.00	1.34
	Max	51.20	11.80	1.39	3.47
RZ	$\bar{x} \pm$ SD	141.73 ± 121.29	52.75 ± 45.21	0.56 ± 0.44	3.38 ± 1.29
	Min	0.00	0.00	0.00	0.81
	Max	374.40	128.70	1.24	4.77

Abbreviations: GLSP—Grasslands on slope and plain, GLS—Grassland on slope, GLP—Grassland on plain, AL—Arable land, FL—Forest land, RZ—Riparian zone, EN—Earthworm number, EB—Earthworm biomass, H—Shannon's index of biodiversity, NCER—Net carbon exchange rate.

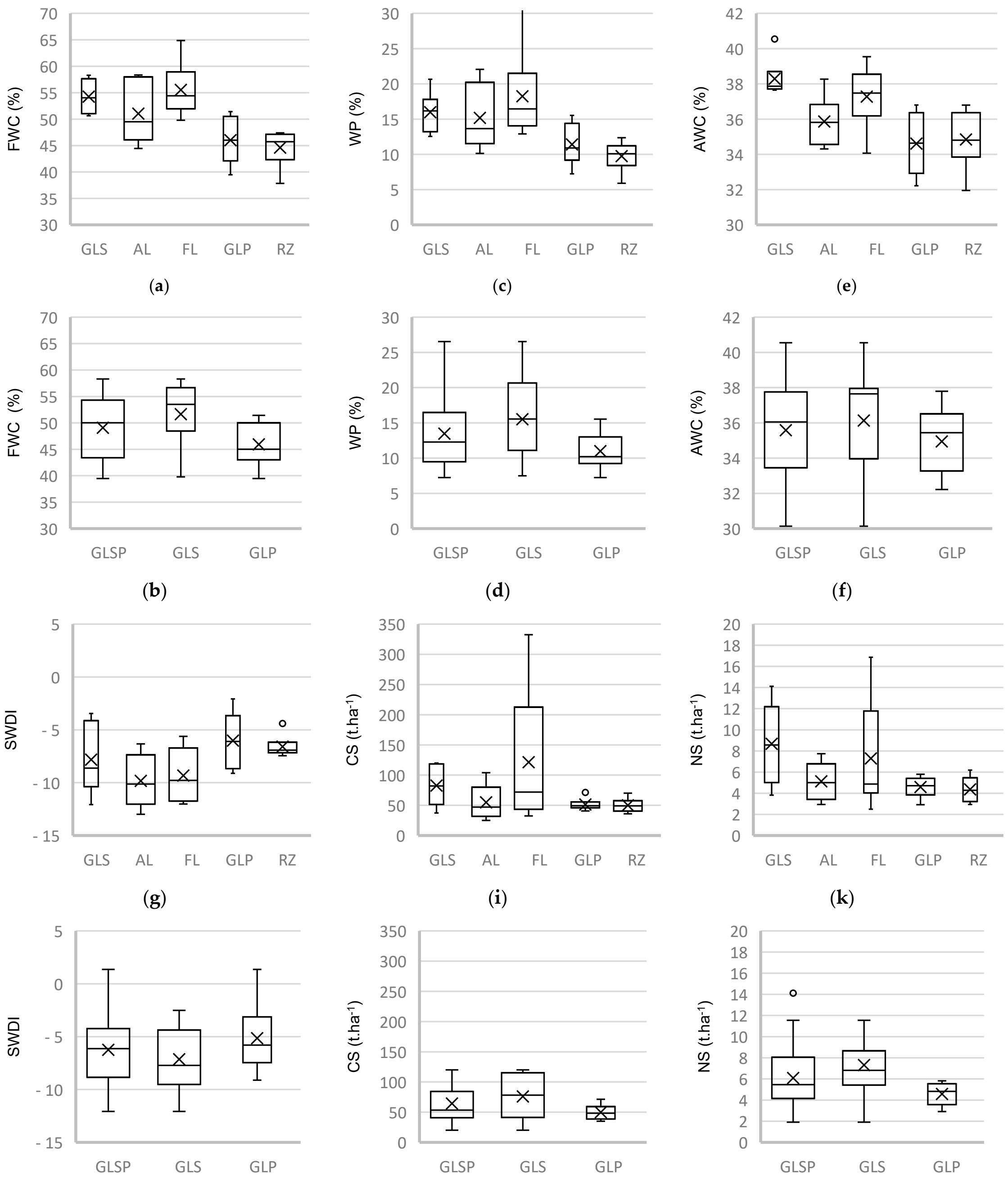
In the case of physical properties, GLP soils were characterized by a lower content of clay and silt particles compared to GLS soils, and conversely, they had a higher content of sand particles. The gravel content was, on average, higher in GLS soils. The average soil temperature and soil moisture were higher in GLP soils, which were also mostly shallower compared to GLS soils in terms of DPR characteristic.

Among all ecosystems, we recorded the most vital characteristics for the presence of earthworm community in GL soils. The highest numbers (438.4 ind.m^{-2}), biomass (211.8 g.m^{-2}), and H (1.2) were present in GLP soils while the lowest ones were found in AL or FL soils. When comparing soils of four different ecosystems (GL, AL, FL, RZ), we recorded the highest maximum or minimum value in GL for some characteristics, such as pH. FL stands out with higher SOC, NT, and Mg reserves. However, the best quality of organic matter was found in AL soils, where we recorded the lowest soil respiration, which was the highest in GL soils. AL stands out with the highest available P and K reserves. Regarding physical properties, FL soils were, on average, characterized by a higher content of clay, silt, and gravel and the lowest BD, which was the highest in GL soils. RZ soils had a higher content of sand. AL soils were characterized by both higher PD and the highest mean soil temperature values. In turn, GL soils had both higher soil moisture and PR.

The FWC, WP, and AWP indicators showed the same trends among ecosystems. We found the highest mean FWC for FL soils (55.5%), followed by GLS soils (54.3%). However, the highest and therefore most favorable SWDI index was calculated for GLP soils.

Among all ecosystems, the highest mean C stock value was found in FL soils (121.5 t.ha^{-1}) followed by GLS soils (76 t.ha^{-1}). However, the median value was higher in GLS soils (82.2 t.ha^{-1}) than in FL soils (72.0 t.ha^{-1}). The mean N stock was higher in GLS soils (8.7 t.ha^{-1}), but again with the highest maximum value found in FL soils (16.9 t.ha^{-1}), for CS (332.4 t.ha^{-1}). Lower stocks were found in other ecosystems (AL, GLP, and RZ).

Figure 2 shows the calculated hydrological indicators and carbon and nitrogen stocks in soils of different ecosystems (GL, AL, FL, and RZ).



(**a**) (**c**) (**e**)

(**b**) (**d**) (**f**)

(**g**) (**i**) (**k**)

(**h**) (**j**) (**l**)

Figure 2. Hydrological indicators and carbon and nitrogen stocks under different land uses; (**a**,**b**) Field water capacity, (**c**,**d**) Wilting point, (**e**,**f**), Available water capacity, (**g**,**h**) Soil water deficit index, (**i**,**j**) Carbon stock, (**k**,**l**) Nitrogen stock. Figures (**a**,**c**,**e**,**g**,**i**,**k**) show indicators within 6 slope and 6 plain study sites with localities of different land uses (GLS, AL, FL at slope study sites; GLP, RZ at plain study sites). Figures (**b**,**d**,**f**,**h**,**j**,**l**) show indicators of all GL localities (GLSP), and separately for slope (GLS) and plain (GLP) localities. Abbreviations: GLSP—Grasslands on slope and plain, GLS—Grassland on slope, GLP—Grassland on plain, AL—Arable land on slope, FL—Forest land on slope, RZ—Riparian zone on plain.

3.2. Relationships Between Soil Properties

The correlations between all soil properties are listed in Table 5.

Table 5. Spearman's correlation coefficients among soil properties.

	A	pH/H_2O	pH/KCl	Eh	SOC	SOM	NT	C/N	NCER	Clay	Silt	Sand	Gravel	BD	PD	ST	SM	PR	DPR	EN	EB	H	P	K	Mg	FWC	WP	AWP	SWDI	CS	NS
A	1																														
pH/H_2O	−0.049	1																													
pH/KCl	0.004	0.921 **	1																												
Eh	−0.001	−0.454 **	−0.523 **	1																											
SOC	0.262	−0.171	−0.143	−0.098	1																										
SOM	0.262	−0.171	−0.143	−0.098	1.000 **	1																									
NT	0.449 **	−0.252	−0.16	−0.052	0.858 **	0.858 **	1																								
C/N	−0.17	0.04	−0.109	0.06	0.524 **	0.524 **	0.063	1																							
NCER	−0.342 *	0.136	0.175	−0.132	0.293	0.293	0.129	0.366 *	1																						
Clay	0.099	−0.139	−0.16	−0.193	0.09	0.09	0.196	−0.209	−0.281	1																					
Silt	0.323 *	−0.296	−0.227	−0.174	0.374 *	0.374 *	0.338 *	0.036	−0.213	0.346 *	1																				
Sand	−0.21	0.312	0.301	0.189	−0.378 *	−0.378 *	−0.360 *	−0.033	0.248	−0.661 **	−0.881 **	1																			
Gravel	0.252	0.222	0.218	0.086	0.077	0.077	0.139	−0.029	0.088	−0.076	−0.125	0.142	1																		
BD	−0.248	0.052	0.016	0.28	−0.256	−0.256	−0.215	−0.248	−0.323 *	0.254	−0.161	−0.029	−0.154	1																	
PD	−0.239	0.127	0.118	−0.056	−0.219	−0.219	−0.193	−0.157	−0.244	0.023	−0.149	0.095	−0.27	0.353 **	1																
ST	−0.312	−0.036	−0.063	−0.072	0.037	0.037	−0.162	0.177	−0.108	0.162	0.235	−0.21	−0.078	0.07	−0.108	1															
SM	−0.13	0.081	0.065	−0.03	0.146	0.146	0.213	−0.03	0.303	−0.204	−0.081	0.046	−0.320 *	0.144	0.111	−0.399 *	1														
PR	−0.003	−0.438 **	−0.352 **	0.445 **	0.143	0.143	0.209	−0.122	−0.161	0.159	0.225	−0.24	0.3	0.283	−0.224	0.231	−0.197	1													
DPR	0.058	−0.083	−0.125	0.06	−0.067	−0.067	0.007	−0.063	0.015	0.137	−0.038	−0.092	−0.445 **	0.041	−0.029	−0.196	0.267	−0.053	1												
EN	−0.097	0.072	0.162	0.021	−0.214	−0.214	−0.058	−0.294	−0.166	0.074	−0.109	0.068	−0.265	0.166	0.038	−0.12	0.257	0.168	0.447 **	1											
EB	−0.012	0.095	0.156	−0.016	−0.232	−0.232	−0.054	−0.312	−0.091	0.01	−0.095	0.073	−0.265	0.051	0.002	−0.242	0.337 *	0.036	0.515 **	0.921 **	1										
H	0.004	0.2	0.206	0.049	−0.028	−0.028	−0.006	0.021	−0.016	0.156	−0.105	0.008	−0.115	0.188	0.274	−0.335 *	0.306	0.031	0.313	0.516 **	0.539 *	1									
P	−0.08	0.341 *	0.238	−0.204	−0.317	−0.317	−0.256	−0.139	−0.141	0.153	−0.326 *	0.205	−0.097	0.038	0.243	−0.137	−0.154	−0.284	0.105	0.093	0.118	0.172	1								
K	0.317	−0.166	−0.064	0.214	0.255	0.255	0.359 *	0.001	−0.066	0.019	−0.068	0.032	0.157	−0.176	0.009	−0.189	−0.216	0.175	0.049	−0.015	0.077	0.206	0.275	1							
Mg	0.122	0.438 **	0.449 **	−0.388 *	0.370 *	0.370 *	0.262	0.213	0.142	−0.066	0.159	−0.081	0.028	0.017	0.128	0.027	0.129	−0.297	−0.287	−0.197	−0.184	0.022	−0.093	−0.117	1						
FWC	0.226	−0.328 *	−0.311	−0.188	0.431 **	0.431 **	0.435 **	0.039	−0.216	0.751 **	0.791 **	−0.967 **	−0.121	0.023	−0.118	0.209	−0.098	0.229	0.11	−0.079	−0.083	−0.019	−0.124	0.089	0.048	1					
WP	0.207	−0.286	−0.298	−0.19	0.408 *	0.408 *	0.438 **	0.006	−0.23	0.857 **	0.667 **	−0.910 **	−0.138	0.106	−0.082	0.166	−0.1	0.197	0.139	−0.046	−0.064	0.035	−0.026	0.093	0.032	0.973 **	1				
AWC	0.390 *	−0.222	−0.149	−0.199	0.362 *	0.362 *	0.307	0.099	−0.088	0.119	0.925 **	−0.698 **	−0.011	−0.406 *	−0.249	0.193	−0.117	0.108	−0.096	−0.177	−0.098	−0.159	−0.319	−0.008	0.129	0.617 **	0.469 **	1			
SWDI	−0.174	0.227	0.235	0.041	−0.073	−0.073	−0.031	−0.017	0.344 *	−0.636 **	−0.338 *	0.483 **	−0.188	−0.002	0.185	−0.439 *	0.818 **	−0.241	0.102	0.252	0.339 *	0.279	−0.074	−0.172	0.08	−0.568 **	−0.591 **	−0.238	1		
CS	0.111	−0.13	−0.107	−0.092	0.829 **	0.829 **	0.694 **	0.381 *	0.074	0.223	0.358 *	−0.437 *	−0.234	0.155	−0.033	0.132	0.284	0.18	0.124	0.062	0.015	0.171	−0.274	0.154	0.324 *	0.462 **	0.469 **	0.229	0.001	1	
NS	0.19	−0.147	−0.075	−0.075	0.579 **	0.579 **	0.697 **	−0.107	−0.116	0.294	0.28	−0.375 *	−0.313	0.319	0.089	−0.053	0.445 **	0.182	0.212	0.205	0.165	0.231	−0.124	0.155	0.256	0.395 **	0.433 **	0.095	0.133	0.837 **	1

pH—Soil reaction, Eh—Redox potential, SOC—Soil organic carbon, SOM—Soil organic matter, NT—Nitrogen total, C/N—Carbon to nitrogen ratio, NCER—Net carbon exchange rate, BD—Bulk density, PD—Particle density, ST—Soil temperature, SM—Soil moisture, PR—Penetrometric resistance, DPR—Depth of penetrometric resistance measurement, EN—Earthworm number, EB—Earthworm biomass, H—Shannon's index of biodiversity, FWC—Field water capacity, WP—Wilting point, AWC—Available water capacity, SWDI—Soil water deficit index, CS—Carbon stock, NS—Nitrogen stock; * r-values shown in bold are significant at $p < 0.05$; ** r-values shown in bold are significant at $p < 0.01$.

Soil pH had a statistically significant negative relationship with Eh, PR, and positive with available P and Mg. SOC, SOM, and NT were positively correlated with silt content and negatively with sand content, which could reflect in a positive correlation with the calculated FWC, WP, AWC, CS, and NS indicators. In addition, SOC and SOM were positively correlated with available Mg, and NT with available K. Soil organic matter quality, expressed by C/N ratio, was positively correlated with NCER and CS. Regarding biological parameters, NCER was negatively correlated with BD and positively with SWDI, EN and EB were negatively correlated with DPR, and EB itself was also positively correlated with SM. As expected, ST was negatively correlated with SWDI while on the contrary, SM was positively correlated. The other correlations only confirm the relationships resulting from the proposed models.

The results of the ANOVA test of normally distributed data assessing the effect of land use are presented in Table 6.

Table 6. Results of ANOVA for the soil properties by land use (n = 30, df = 4).

Soil Characteristic	Land Use	
	F-Value	*p*-Value
pH/H$_2$O	4.998	**0.004**
pH/KCl	3.214	**0.029**
Silt	6.795	**<0.001**
Sand	5.948	**0.002**
ST	0.311	0.868
SM	1.129	0.365
PR	2.413	0.076
FWC	6.802	**<0.001**
AWC	5.529	**0.002**
SWDI	2.567	**0.063**
NCER	4.362	**0.008**

pH—Soil reaction, ST—Soil temperature, SM—Soil moisture, PR—Penetrometric resistance, FWC—Field water capacity, AWC—Available water capacity, SWDI—Soil water deficit index, NCER—Net carbon exchange rate; *p*-values highlighted in bold are highly statistically significant ($p < 0.001$) and statistically significant ($p < 0.05$).

The statistical analysis showed significant differences between the land uses in case of representative variables of chemical (pH/H$_2$O, pH/KCl), physical (silt, sand, FWC, AWC, SWDI) and biological (NCER) properties. Significant main effects were explored further using the post hoc Tukey test (Table 7).

The HCA (Figure 3) has highlighted two large clusters (A and B). Cluster A contains three sites on Fluvisol that are situated on plains and used as GL and RZ. Two clusters of lower hierarchical order are recognized in B (B1 and B2). Cluster B1 exclusively includes sites situated on slopes used as GL, FL, and AL. Cluster B2 includes nine sites situated on plains and eight situated on slopes with all land use types.

Table 7. Effect of land use on soil properties.

Land Use	pH/H$_2$O	pH/KCl	Silt (%)	Sand (%)	ST (°C)	SM (%)	PR (MPa. cm^{-1})	FWC (%)	AWC (%)	SWDI	NCER (µmol CO$_2$. m^{-2}s^{-1})
GLS	$5.77^{a} \pm 0.87$	$5.56^{ab} \pm 1.00$	$62.72^{c} \pm 6.69$	$24.72^{a} \pm 8.29$	$58.17^{a} \pm 21.95$	$24.27^{a} \pm 10.80$	$1.35^{a} \pm 0.21$	$54.27^{b} \pm 3.15$	$38.22^{b} \pm 1.15$	$-7.82^{a} \pm 3.36$	$1.96^{ab} \pm 0.42$
GLP	$6.85^{ab} \pm 0.53$	$6.31^{ab} \pm 0.76$	$39.38^{ab} \pm 12.27$	$50.25^{bc} \pm 14.12$	$17.47^{a} \pm 7.04$	$25.13^{a} \pm 7.73$	$1.15^{a} \pm 0.31$	$46.02^{a} \pm 4.47$	$34.62^{a} \pm 1.91$	$-6.02^{a} \pm 2.63$	$2.25^{ab} \pm 1.33$
AL	$6.33^{ab} \pm 0.64$	$5.59^{ab} \pm 0.71$	$48.88^{abc} \pm 11.78$	$36.38^{abc} \pm 17.38$	$17.28^{a} \pm 9.83$	$15.70^{a} \pm 6.74$	$0.87^{a} \pm 0.25$	$51.03^{ab} \pm 5.82$	$35.85^{ab} \pm 1.46$	$-9.82^{a} \pm 2.49$	$0.93^{a} \pm 0.79$
FL	$5.88^{a} \pm 0.77$	$5.02^{a} \pm 1.21$	$55.68^{bc} \pm 7.38$	$28.82^{ab} \pm 12.73$	$13.28^{a} \pm 7.40$	$20.82^{a} \pm 10.98$	$1.07^{a} \pm 0.38$	$55.53^{b} \pm 5.26$	$37.28^{ab} \pm 1.80$	$-9.32^{a} \pm 2.55$	$2.44^{ab} \pm 0.88$
RZ	$7.22^{b} \pm 0.50$	$6.69^{b} \pm 0.73$	$37.32^{a} \pm 10.99$	$54.93^{c} \pm 12.01$	$14.77^{a} \pm 5.25$	$21.72^{a} \pm 4.79$	$0.93^{a} \pm 0.32$	$44.58^{a} \pm 3.59$	$34.85^{a} \pm 1.67$	$-6.58^{a} \pm 1.09$	$3.38^{b} \pm 1.42$

Abbreviations: GLS—Grassland on slope, GLP—Grassland on plain, AL—Arable land, FL—Forest land, RZ—Riparian zone, pH—Soil reaction, ST—Soil temperature, SM—Soil moisture, PR—Penetrometric resistance, FWC—Field water capacity, AWC—Available water capacity, SWDI—Soil water deficit index, NCER—Net carbon exchange rate; different letters indicate statistically significant differences according to Tukey's HSD test ($p < 0.05$; mean ± SE; n = 30).

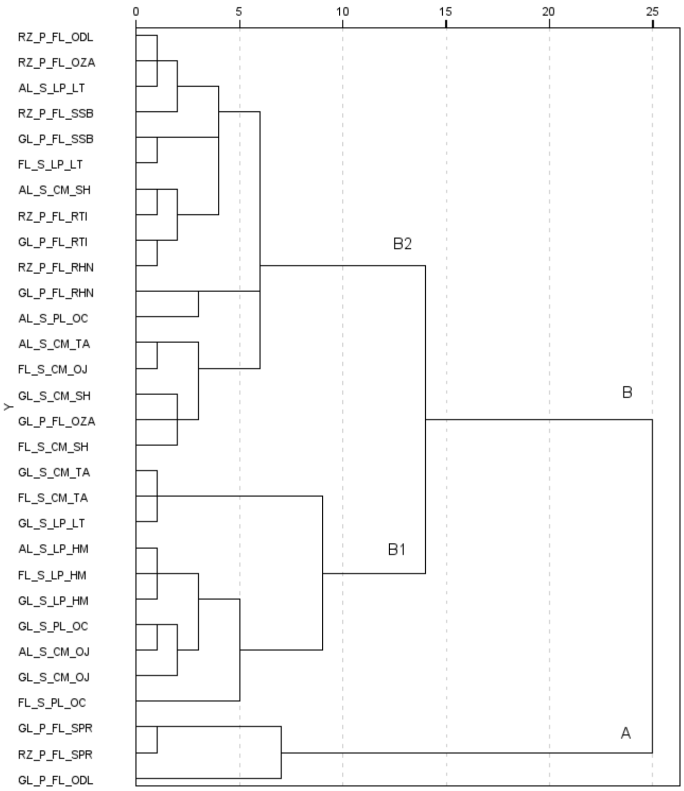


Figure 3. Dendrogram for the hierarchical clustering of sites.

4. Discussion

Soils generally exhibited high variability, which is particularly conditioned by their natural origin. But soil heterogeneity is also affected by ecosystems, land use, and management. Similarly to our study, other authors [47–49] confirmed that spatial variability of soil chemical, biological, and physical properties is significantly affected by both land use and soil type. Usually, long-term intensive land use adversely affects soil properties, having impacts on soil health and provision of ecosystem services [50]. Extensive practices based on ecological principles improve soil properties [51] and subsequently soil supporting and regulating services.

However, this is not generally true. In our study, in the case of earthworms, the positive effect of extensive management forms was confirmed in terms of higher numbers, biomass, and diversity of earthworms in GL soils compared to intensively managed AL soils. This is in line with many studies [52,53]. However, we did not confirm this effect in the case of earthworms in extensively managed FL soils, where earthworm parameters reached similar values to those in intensively managed AL soils. In this case, if the environment is exposed to less pressure, but does not meet the basic requirements of organisms (e.g., soil moisture or temperature), this will affect their presence as well as their management. In addition, Betancur-Corredor et al. [54], based on a global meta-analysis focused on the impact of land use on earthworm communities, concluded that earthworm responses are highly heterogenous and cannot be explained by the individual assessment of climatic, soil-related, or management factors.

Our results showed that ecosystems with different land uses also influence the other chemical soil properties. GLS soils had, among all ecosystems, the highest mean reserve of available Mg, available water capacity, and nitrogen storage. GLP soils excelled in earthworm number, their biomass and diversity, and in SWDI index. On the contrary, GLSs were the worst supplied with available phosphorus.

Phosphorus, as a plant macronutrient, is a key element in photosynthesis, respiration, and frequently limits productivity in both natural and agroecosystems, especially in low-input systems [55]. Although abundant in soils, in both organic and inorganic forms, its availability is restricted [56]. Only a small proportion of the total soil P is available for plant uptake because of fixation. Most P is associated with Al and Fe oxides or hydroxides in acidic soils, and with Ca in calcareous soils [57]. Most P in soil is not readily available to plants. Nutrient limitation to primary productivity is widespread in terrestrial ecosystems, and P is one of the most common limiting elements [58]. Phosphorus availability is often a primary constraint to plant productivity [59]. A solution should be fertilization. A large amount of P geological deposits has been mined to produce fertilizers. Unfortunately, easily mineable P deposits are finite and could be depleted in the next 50–100 years [60]. Therefore, the focus is currently shifting to the use of organic amendments [61]. However, the real problem is that the availability of P from applied sources tends to decrease because of ambiguity and complexity of retention and release mechanisms in soil [62]. Therefore, developing sustainable management strategies to better exploit soil P cycling are urgently needed [63]. This makes phosphorus management a major issue for future nutrients' security for all soils, not just GL soils.

A different situation was observed in the reserves of available Mg, abundant in the soils of all monitored localities and in all ecosystems. Geochemical distribution of Mg in agricultural soils of Europe has shown high Mg concentrations in soil developed over mafic lithologies and in carbonate-rich regions [64], as occurred in our localities. In this case, lithology plays a key role in Mg availability and nutritional status. Available K was measured at a relatively good level in soils at study sites, but the lowest content among ecosystems was registered in GLP. The availability of K can differ substantially between soils. K can become a limiting factor, especially on sandy soils with little clay content [65]. GLP soils of our study, similarly to RZ soils, were developed on river alluvia, characterized by higher sand content (mean sand content in GLP localities was 49.8%; in RZ localities, 54.9%).

Soils comprise a reservoir of biodiversity, providing many benefits for human well-being. Poor land management, including intensification and deforestation, can cause a decline in soil biodiversity and a reduction in these benefits [66]. For the assessment of the earthworm community, we used earthworm abundance and biomass as indicators, since they are indices of soil health and ecosystem services for different ecosystems [67]. The study revealed the highest number, biomass, and diversity of earthworms in GLP soils, followed by FL, GLS, RZ, and AL. These results are consistent with many authors who also found the higher earthworm abundance and biomass at extensively used ecosystems such as grasslands or forests compared to intensively used arable land [68,69]. Spurgeon et al. [70], based on a meta-analysis of 16 studies, reported an average earthworm number of 56.3 ind.m^{-2} under arable land (49.6 ind.m^{-2} in AL in our study) and 229 ind.m^{-2} under grasslands (226.7 ind.m^{-2} in GLP in our study).

As expected, we also found an impact of ecosystem type on the hydrological properties, carbon and nitrogen storage. Soils of extensive ecosystems (FL and GL) had higher water retention capacity and carbon and nitrogen storage than AL soils, as was reported by other researchers [71,72]. However, since the AL on the slopes of the study sites were not very intensively managed (some of them were even organically farmed), the differences between ecosystem types were not found to be very significant. In some cases, these properties were better in AL soils than in GLP and RZP soils. This shows that management intensity can strongly affect soil properties. FL and RZ soils are not disturbed, and GL soils are less disturbed than cultivated ones. In extensive ecosystems, the dense root system of plants provides rich organic matter by influencing the amount of carbon and nitrogen storages, and also supports greater water storage capacity [73]. GLS and FL excelled in C stock. It is estimated that approximately 10–30% of the global soil organic carbon is stored in grassland soils [74]. In our study, the mean value of SOC stock in GLS soils was lower than in FLS soils, while the opposite was true for the median value. The C stock in soil is highly variable and depends on many environmental conditions and land uses. Canedoli et al. [75], in alpine region, found out that the typologies of habitats have a significant effect on SOC stock. In their study, mixed broadleaf forests store the highest SOC, followed by grasslands, mixed coniferous forests, and spruce forests. Similarly, in the temperate Himalayas, Kumar et al. [76] found the highest total organic carbon pools in the soil under natural forests followed by natural grasslands. However, in addition to land use, the influence of management must also be considered. Many works have shown that organic carbon stocks in soils of grasslands have been largely depleted worldwide due to mismanagement. On the other hand, right management practices could potentially increase soil organic carbon stocks [77]. Grasslands thus play an important role in the global C balance and impact the global climate [78]. High levels of organic carbon can help maintain and improve soil fertility and water availability [79]. In our study, SOC was positively correlated with hydrological indicators such as FWC and WP. Soil water is the most important factor limiting plant growth [80]. Thus, grasslands also play an important role in the water cycle.

5. Conclusions

Understanding how land use and landscape unit influence soil properties can lead to improved soil management, particularly in environments that have undergone changes caused by climate and human activities. We found that similarly to land use patterns, environmental properties and altitude had significant effects on soil.

GL soils are very diverse: most of their characteristics showed large variability, more pronounced in GLS soils than in GLP soils. The properties of GL soils are different from those of other ecosystems and land uses. GL soils provide satisfactory services in addition to many other services that are currently undervalued. Among essential nutrients, we found low availability of phosphorus in all ecosystems, but the lowest in GLS soils. Nutrient deficit should always be considered in soil management. A long-term deficit can negatively disrupt mutual interaction and linkages between properties and, beyond a certain limit, can negatively impact ecosystem services. Therefore, further research should be focused on options for increasing soil phosphorus supply through management measures and adding organic additives to the soil.

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