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Evaluation of Microbiological and Chemical Properties of Soils as a Result of Anthropogenic Denudation

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Abstract: Excessive agricultural intensification adversely affects soil quality, particularly in hilly terrain, leading to increased erosion. Anthropogenic denudation, intensified by tillage erosion, results in the displacement of soil material from hilltops and shoulders to their bases. The research hypothesis posits that tillage erosion adversely affects the microbiological and chemical properties of soils, especially at the hilltops of intensively cultivated areas. The study aimed to assess the microbiological and chemical properties of Luvisols cultivated under conventional plowing in the moraine region of the Southern Krajna Lakeland, Poland. The evaluation focused on the results of soil sample analyses taken from the hilltops and foothills of eroded mounds. Microbiological investigations included determining the abundance of actinomycetes, filamentous fungi, heterotrophic bacteria, cellulolytic microorganisms, copiotrophs, and oligotrophs. Additionally, pH values and the contents of phosphorus, potassium, magnesium, total organic carbon, and nitrogen were determined. A higher abundance of bacteria, actinomycetes, and copiotrophs was observed at the foothills. Statistically significant differences due to slope effects were noted for all chemical parameters, with higher concentrations of organic carbon, nitrogen, potassium, and phosphorus found in the foothill areas. Understanding denudation processes can contribute to sustainable soil resource use and agrocenosis conservation.

Keywords: denudation; soil microbiota; soil degradation; chemical properties of soils; Luvisols; soil biodiversity



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1. Introduction

The increasing pressure on natural resources, driven by population growth and the consequent need to enhance food production, is one of the contemporary challenges facing the maintenance, protection, and restoration of agrobiocenosis [1,2]. Agricultural production itself is critically tied to the soil; initially, the growth of production relied on expanding the cultivated land area (currently approximately 1.6 billion hectares). Over time, however, investments in agricultural intensification, understood as an increase in crop production per unit area, have increased [3]. Such a condition has the potential to disrupt the sustainable development of agriculture, characterized by the system's capacity to consistently uphold food production without exerting degradative impacts on the natural environment [4]. Sustaining global efforts to monitor changes occurring directly in the soil and indirectly in agriculture allows for early identification of threats related to environmental protection and the global food production system. There is a scientific consensus confirming that systematic monitoring of soil erosion is a key element in the effective implementation of sustainable agricultural practices. Understanding erosion processes and their impact on soil structure and chemical and microbial composition is fundamental to achieving a sustainable ecological balance [5]. Detailed microbiological and chemical analyses of soil enable an understanding of the causes, prevention, minimization,

and combatting of the adverse effects of soil degradation [6–8]. To this end, tools based on indicators of potential risk of soil productivity loss have been implemented to enable the predictive control of agroecosystems [9].

The intensification of agricultural production, particularly in developed countries, coupled with the occurrence of extreme weather events, has the potential to disrupt water relations and induce alterations in the soil environment, including phenomena such as cracking, crusting, and degradation of soil structure and aggregation [8,10]. The erosion rate is not only dependent on the topography and climatic conditions. Numerous factors influence the intensity of soil degradation processes, including soil type, texture, aggregate structure, cultivation system, cultivation practices, and the type of cultivated plant [9,11]. An additional factor influencing the acceleration of soil erosion processes is the socio-economic factors that impact the selection of environmentally unfavorable practices within the farming system [12]. The problem of soil erosion is so significant that it has been classified as the greatest global threat to soil functionality and health, thus affecting humanity's food security [13,14].

One of the key indicators of soil quality is soil microbiota. A detailed understanding of the dynamics of changes within specific groups of microorganisms in the soil environment is crucial, given that soil microbiota constitutes a significant component of the ecosystem's response to erosive processes [15]. The rapid response of soil microorganisms is attributed to their reaction to the degradative impact of erosive processes on abiotic factors (pH, particle size composition, carbon, and nitrogen content), which directly shape the populations of fungi and bacteria [16]. Subsequently, alterations and disturbances in soil microbiota result in changes related to the availability of elements, nitrogen and phosphorus binding, organic matter accumulation, and mass and energy cycling. These processes ultimately exert a negative impact on the physiological stress of plants, leading to a decline in crop yield [17,18].

Luvisols, the prevailing soil group in the lowland and upland areas of Poland, significantly impact agricultural production due to their classification as relatively fertile soils [4]. Currently, soil degradation in Europe is a recognized and growing issue. This phenomenon is particularly noticeable in moraine areas, where slope processes lead to the displacement of soil material from the summit of the slope towards the foothills [6,19]. Inappropriate cultivation practices intensify the denudation effect on the soil, recognized as the surface lowering of the slope in a terrain with relief. The process of slope erosion is comprehensive and can involve the entire soil profile, ranging from the topsoil layer to the bedrock [6,20]. Anthropogenic denudation (accelerated erosion) is recognized as one of the more serious threats to the geoenvironment, given its impact on the productivity of plant production [2]. It is worth noting that areas subjected to significant anthropogenic pressure, particularly since the beginning of human settlement, are especially vulnerable. Currently, these processes intensify due to deforestation, extensive drainage networks, and, above all, as a result of agricultural intensification and the use of advanced agricultural machinery. This accelerates the truncation of pedons and leads to the exposure of deeper genetic horizons in soil profiles on elevated terrain, potentially resulting in physical, chemical, and biological changes in soil properties. This phenomenon applies not only to the summit but also to the foothills of the hillslope [3,6,21].

Changes in soil management practices can affect soil morphology, water retention, chemical properties, and biological activity. In particular, tillage practices lead to the intensification of slope processes [3,22,23]. Soil erosion leads to transformations of the soil cover of young morainic terrains of mesoregions in northern Poland. Main alterations relate to soil truncation on summits of slopes, whereas at footslopes and toeslopes and within local depressions, colluvial material is accumulated [24,25].

Given the challenges posed by climate change, a growing population, and soil degradation, it is essential to focus more on protecting and monitoring agricultural soils. These soils, which are particularly susceptible to erosion processes, require increased attention to ensure sustainable crop production. Monitoring fields in moraine terrain is among the

top priorities for modern agriculture in Poland. Sustainable agricultural practices enable more efficient use of production resources and better environmental protection. Therefore, it is essential to have knowledge about the actual quality of soils and biological activity, especially in soils prone to erosion.

The research hypothesis states that agricultural erosion has a detrimental effect on the microbiological and chemical properties of soils subjected to intensive cultivation under a conventional agricultural system. This phenomenon is particularly pronounced in regions characterized by undulating topography, such as hilly or moraine landscapes. Under such topographic conditions, the erosive forces associated with agricultural activities are amplified because the post-glacial terrain promotes the formation of runoff paths for soil particles, nutrients, and organic matter. The undulating nature of the terrain contributes to accelerating erosion, intensifying the movement of essential components and affecting the composition of the soil microbiota.

The aim of the study was to assess the microbiological and chemical properties of the topsoil and subsoil layers of Luvisols subjected to anthropogenic denudation in the moraine region of the Southern Krajna Lakeland (northern Poland). The assessment included the quantification of actinobacteria, the total count of fungi and bacteria, as well as the count of copiotrophic, cellulolytic, and oligotrophic microorganisms in the soil at the summit and foothills of the hills. The study compared the content of plant-available forms of phosphorus, potassium, and magnesium, as well as the content of total organic carbon and nitrogen, along with pH values. In addition, the grain size composition was analyzed and the electrical conductivity (EC) of soil was determined. Comparisons of microbiological and physicochemical parameters were conducted for two genetic horizons: topsoil (0–30 cm) and subsoil (30–50 cm). Monitoring potential microbiological and chemical changes may contribute to a better understanding of the erosion dynamics in Luvisols subjected to intense anthropogenic pressure in areas with diverse topography.

2. Materials and Methods

2.1. Study Sites and Sampling

The research was conducted in the mesoregion of the South Baltic Lakeland (northern Poland)—specifically, the Southern Krajna Lakeland, with an average elevation of 115.6 m above sea level [26,27]. The climate of the studied region is temperate, with an average annual temperature of 7.8 °C (average annual minimum temperature of 3.8 °C and average annual maximum temperature of 12.8 °C) and a long-term average annual rainfall of 504 mm. Farmers do not implement proper crop rotation on the examined fields, which would enrich the soil with organic matter serving as a water reservoir. Winter wheat and rapeseed dominate the crop rotation on the surveyed fields. Unfortunately, farmers choose this option to ensure the financial stability of their farms. While this positively affects the profitability of production and enables farm development, it deteriorates soil fertility and the potential for biodiversity.

Three arable fields were selected (designated as R, S, T) that exhibited the typical mosaic topography characteristic of this area (Figure 1).

A total of 6 soil pits were excavated, representative of the soil cover in the studied region. All soil samples were collected after the winter wheat harvest, which was fertilized with a similar dose of NPK (average NPK fertilizer consumption was 140 kg: 80 kg N, 25 kg P, 35 kg K). A conventional cultivation system and similar agrotechnical treatments were applied uniformly across all locations. For each location (arable field), two soil pits were excavated: one at the summit of the hill and another at its foothills. Soil samples for testing were taken from the hills on the northern side of slopes ranging from 82 to 150 m above sea level. The length of the slope ranged from 90 to 150 m (Figure 2).

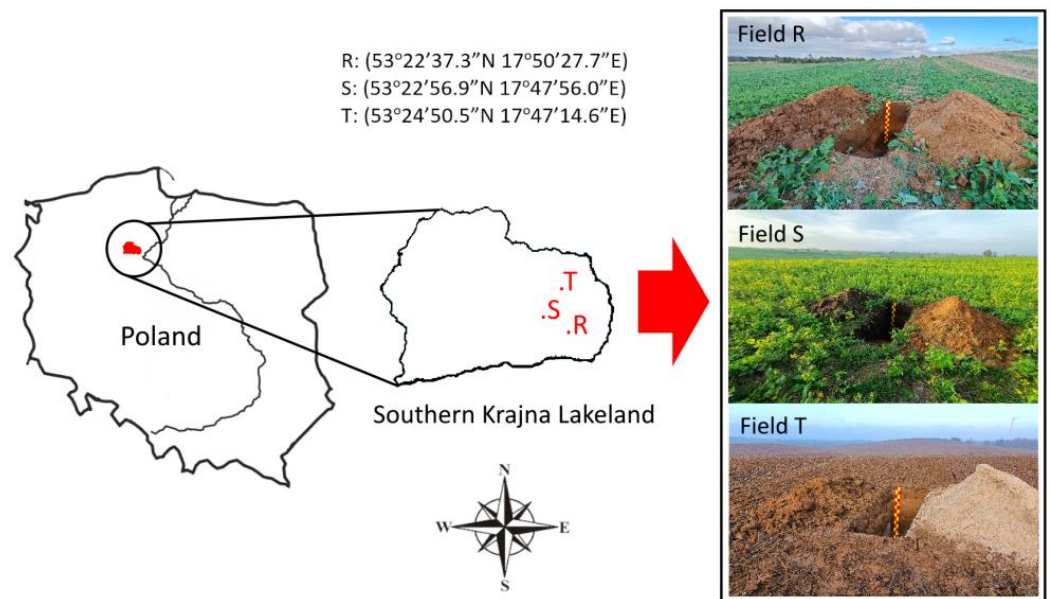


Figure 1. Location of tested fields (photos of profile pits at the foot of the hills).

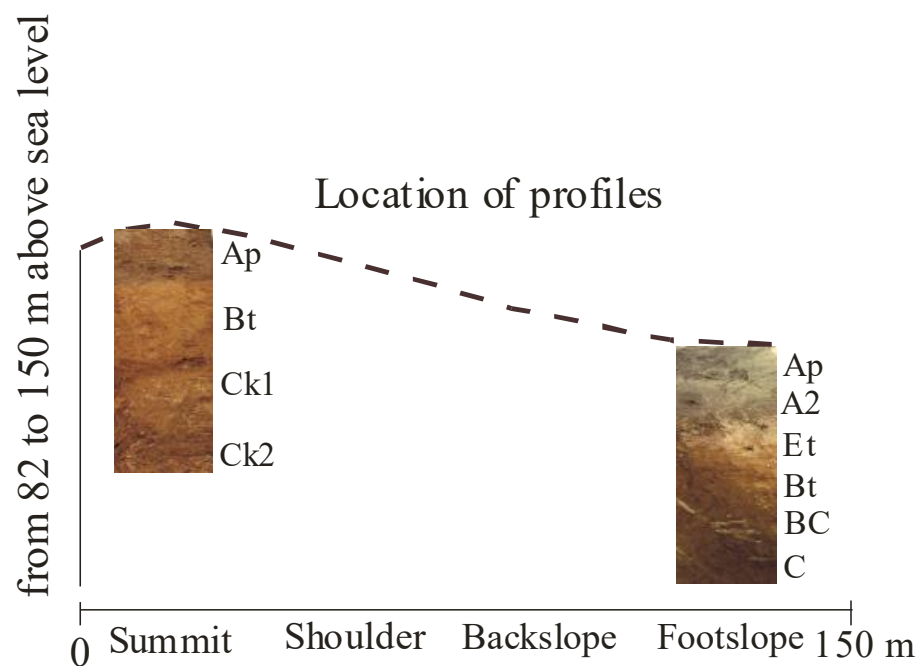


Figure 2. Locations of soil profiles (the example given here is site R). Abbreviations: Ap—plow horizon, A2—hummus horizon, Et—luvic horizon, Bt—argic horizon, BC—transitional horizon between argic and parent material, C—parent material, Ck1—parent material with calcium carbonate, Ck2—second parent material with calcium carbonate.

The locations of the soil pits were distant from buildings and roads. From each soil pit, soil samples were collected from two genetic horizons (Ap—surface and subsoil), corresponding to depths of 0–30 cm and 30–50 cm, respectively, in October 2022 (Table 1).

Table 1. The compilation of media used for the isolation and cultivation of microorganisms from the investigated soil samples.

Site	Profile	Soil Classification WRB 2022 [28]	Sampling
R	Ap-Bt-Ck1-Ck2 Ap-A2-Et-BC-C	Epicutanic Luvisol Haplic Luvisol	A1—Summit: B1—Ap horizon; B2—Bt horizon A2—Footslope: B1—Ap horizon; B2—A2 horizon
S	Ap-Ck1-Ck2-Ck3 Ap-A2-Et-EB-Bt-C	Calcaric, Eutric Regosol Haplic Luvisol	A1—Summit: B1—Ap horizon; B2—Ck1 horizon A2—Footslope: B1—Ap horizon; B2—A2 horizon
T	Ap-Ck1-Ck2-2Ck Ap-A2-Et-EB-Bt1-Bt2-C	Calcaric, Eutric Regosol Haplic Luvisol	A1—Summit: B1—Ap horizon; B2—Ck1 horizon A2—Footslope: B1—Ap horizon; B2—A2 horizon

These samples were stored in plastic containers, allowing gas exchange, then cooled to 4 °C and transported to the laboratory. Soil samples for chemical analysis were placed in plastic bags, air-dried, and sieved through a 2-mm mesh screen.

2.2. Microbiological Analyses

Microbiological analyses of soil samples included quantitative determinations for the following groups of microorganisms:

1. Actinobacteria (Ac),
2. Total bacterial count (B),
3. Total fungal count (Ff),
4. Cellulolytic bacteria (Ce),
5. Oligotrophs (Ol),
6. Copiotrophs (Co).

For all determinations, 10 g of soil were weighed and introduced into 90 mL of Ringer's solution. Subsequently, the samples were shaken for 25 min at room temperature. Following the homogenization of the suspension, a series of 10-fold dilutions (10^{-1} to 10^{-7}) were prepared. Subsequently, 1000 μ L of the soil solution was transferred onto dedicated selective media (Table 2).

Table 2. The compilation of media used for the isolation and cultivation of microorganisms from the investigated soil samples.

Tested Groups of Microorganisms	Applied Medium	Reference
Ac	Modified yeast extract-glucose medium (YGA)	[29]
B	Standard nutrient agar	[30]
Ff	Rose-Bengal agar with 30 μ g mL ⁻¹ streptomycin	[30]
Ce	Agar containing 0.1% sodium carboxymethylcellulose	[31]
Ol	Modified medium with limited nutrients	[32]
Co	Modified medium with additional nutrients	[32]

The incubation of microorganisms was carried out at 25–28 °C for 4 days for B, Ff, Co, and Ce; 10 days for actinobacteria, and 14 days for oligotrophic microorganisms. All analyses were performed in three replicates. The count of colony-forming units (cfu) obtained was determined per 1 g of soil dry matter. ($\text{cfu} \times \text{g}^{-1}$ d.m. of soil).

2.3. Soil Sample Chemical Analyses

The texture of soil samples was determined using a laser diffraction particle size analyzer (Mastersizer 2000, Malvern Instruments, Malvern, UK). Potentiometric measurements of pH values were conducted in a 1 M KCl (1:2.5 *w/v*) solution [33] using a pH Meter (CP-551—Elmetron, Zabrze, Poland). The total organic carbon (TOC) and total nitrogen (TN) content were determined using a CN dry combustion analyzer (Vario Max CN, Elementar

Analysensysteme GmbH, Hanau, Germany). The content of available magnesium (Mg) was assessed using the Schachtschabel method [34]. The contents of available forms of phosphorus (P) [35] and potassium (K) were determined by the Egner–Riehm method [36]. The content of forms available to plants was determined by atomic absorption spectroscopy and atomic emission spectroscopy using a Thermo Solaar S4 Atomic Absorption Spectrometer (Thermo Electron Corporation, Waltham, MA, USA). Measuring ECs with a conductivity meter in a soil-water extract was based on a fixed soil:solution ratio (1:5). The water-soluble forms of cations were based on the extraction with distilled water. Soluble salts were measured by the 1:5 (*v:v*) soil:de-ionized water extraction method. All the measurements were performed in three replications. Finally, Ca, Mg, K, and Na contents were measured using a Thermo Solaar S4 Atomic Absorption Spectrometer (Thermo Electron Corporation, Waltham, MA, USA).

2.4. Statistical Analyses

The obtained results of microbiological and chemical parameters underwent statistical analysis through a two-way analysis of variance (ANOVA). The first factor (A) was associated with the location of the soil pit (A1—summit and A2—footslope), while the second factor was related to the depth (B1—surface level 0–30 cm and B2—subsurface level 30–50 cm). To assess the significance of these factors and their mutual interactions, Tukey’s post hoc test with a 95% confidence interval was conducted, enabling a comparison of the mean values of the analyzed parameters.

In order to better explain the soil variation in terms of selected parameters (biological and chemical) and the relationship between them, the multivariate statistical method Principal Component Analysis (PCA) was used. The use of PCA also made it possible to present correlations between the studied parameters. Differences between objects were analyzed using PCA based on the mean values of all investigated soil features. Two principal components (PC1 and PC2) were used to rank the cases. A cluster analysis (CA) was also carried out. CA allowed the separation of groups of sites based on the diversity of variables, which was graphically presented in the form of a dendrogram. The Ward method [37] was employed to calculate the distances between individual clusters. All statistical analyses were conducted using Statistica 12 PL software from StatSoft [38].

3. Results

3.1. Microbiological Analysis

Analyses of microbiological data revealed statistically significant differences in the abundance of selected microbial groups both between surface and subsurface levels and between locations at the summit and footslope (Table 3). Concerning the overall bacterial count, test field T exhibited the most substantial decrease between surface levels, with a notable increase in colony-forming units (cfu) in soil samples collected at the footslope by 674.20% ($LSD_{0.05} = 10.868$).

A similar phenomenon was also observed for actinobacteria in field S, where a statistically significant decrease in cfu was noted with an increase in horizontal position in the surface level ($LSD_{0.05} = 0.431$) and in the case of fungi abundance (field T). Tendencies related to changes in bacterial abundance between the examined levels at the summit and foothill were also observed; in all cases, a decrease in cfu was noted with the depth of sample collection.

Table 3. The number of bacteria, fungi, and actinomycetes in the soil, depending on the soil profile and location on the slope.

Level of Factor B	Test Site R			Test Site S			Test Site T		
	Level of Factor A *						A1	A2	Mean
	A1	A2	Mean	A1	A2	Mean			
Heterotrophic bacteria (B) (10^6 cfu g^{-1})									
B1	27.3 ^a	23.0 ^a	25.2 ^a	18.7 ^a	18.7	18.7 ^a	3.1 ^a	24.0 ^a	13.6 ^a
B2	6.1 ^a	5.2 ^a	5.7 ^b	2.3 ^b	2.4	2.3 ^b	2.5 ^a	1.3 ^b	1.9 ^b
Mean	16.7	14.1		10.5	10.5		2.8	12.6	
LSD _{0.05}	A = n.s.; B = 5.499; A/B = n.s.; B/A = n.s.			A = n.s.; B = 3.991; A/B = n.s.; B/A = n.s.			A = 7.685; B = 7.685; A/B = 10.868; B/A = 10.868		
Actinobacteria (Ac) (10^5 cfu g^{-1})									
B1	28.7 ^a	30.7 ^a	29.7 ^a	18.0 ^a	28.7 ^a	23.3 ^a	27.0 ^a	52.0 ^a	3.9 ^b
B2	18.7 ^a	26.3 ^a	22.5 ^a	8.6 ^b	6.8 ^b	7.6 ^b	2.0 ^a	10.8 ^a	6.4 ^a
Mean	23.7	28.5		18.6	12.3		14.0	31.0	
LSD _{0.05}	A = n.s.; B = n.s.; A/B = n.s.; B/A = n.s.			A = 0.305; B = 0.305; A/B = 0.431; B/A = 0.431			A = 1.252; B = 1.252; A/B = n.s.; B/A = n.s.		
Filamentous fungi (Ff) (10^5 cfu g^{-1})									
B1	5.0 ^a	3.0 ^a	4.0 ^a	3.0 ^a	4.0 ^a	3.2 ^a	2.0 ^a	13.0 ^a	7.5 ^a
B2	1.0 ^a	1.0 ^a	1.4 ^b	1.0 ^a	2.0 ^a	1.2 ^b	1.0 ^b	1.0 ^b	1.0 ^b
Mean	3.1	2.3		1.6	2.8		1.30	0.7	
LSD _{0.05}	A = n.s.; B = 0.133; A/B = n.s.; B/A = n.s.			A = 0.108; B = 0.108; A/B = n.s.; B/A = n.s.			A = 0.436; B = 0.436; A/B = 0.616; B/A = 0.616		

* Levels of factor A: A1 (summit), A2 (footslope); Levels of factor B: B1 (surface level), B2 (subsurface level); LSD—Least Significant Difference, significance of differences tested with Tukey’s test at $p \leq 0.05$; n.s.—not significant; ^{a,b}—letters in columns indicate significant differences at $p \leq 0.05$.

In the case of trophic groups of microorganisms (Ce, Co, and Ol), the research results demonstrated greater diversity (Table 4). The abundance of cellulose-degrading microorganisms was higher at the summit of the slope than at its footslope. This trend reversed in soil samples from subsurface levels, where a higher abundance of cellulolytic microbes was observed at the foot of the slope. On the other hand, no statistically significant differences were found in any of the tested fields for this trophic group. Copiotrophs, however, predominated at the foot of the slope, regardless of the surveyed location. The soil samples from field R revealed statistically significant differences ($LSD_{0.05} = 13.543$) between the summit and the footslope in the presence of oligotrophic microorganisms. These microbes, inhabiting an environment with a reduced supply of energy substrates, clearly dominated on the slope of the field.

Table 4. The number of cellulolytic, copiotrophic, and oligotrophic microorganisms in the soil, depending on the soil profile and location on the slope.

Level of Factor B	Test Site R			Test Site S			Test Site T		
	Level of Factor A						A1	A2	Mean
	A1	A2	Mean	A1	A2	Mean			
Cellulolytic microorganisms (Ce) (10^6 cfu g^{-1})									
B1	8.0 ^a	5.3 ^a	6.7 ^a	6.3 ^a	3.3 ^a	4.8 ^a	5.1 ^a	4.8 ^a	5.0 ^a
B2	1.0 ^a	1.2 ^a	1.1 ^b	1.4 ^b	3.3 ^a	1.6 ^b	0.5 ^a	0.8 ^a	0.6 ^b
Mean	4.5	3.3		3.9	1.7		2.8	2.8	
LSD _{0.05}	A = n.s.; B = 2.255; A/B = n.s.; B/A = n.s.			A = 1.360; B = 1.360; A/B = 1.923; B/A = 1.923			A = n.s.; B = 4.218; A/B = n.s.; B/A = n.s.		

Table 4. Cont.

Level of Factor B	Test Site R			Test Site S			Test Site T		
	Level of Factor A								
	A1	A2	Mean	A1	A2	Mean	A1	A2	Mean
Copiotrophic microorganisms (Co) (10^6 cfu g^{-1})									
B1	14.3 ^a	24.7 ^a	19.5 ^a	15.0 ^a	19.3 ^a	17.2 ^a	11.3 ^a	24.0 ^a	15.5 ^a
B2	2.9 ^a	6.0 ^a	4.4 ^b	2.6 ^a	3.2 ^a	3.0 ^b	1.1 ^a	1.3 ^a	1.2 ^b
Mean	8.6	15.3		8.8	11.3		4.0	12.7	
LSD _{0.05}	A = n.s.; B = 9.367; A/B = n.s.; B/A = n.s.			A = n.s.; B = 6.255; A/B = n.s.; B/A = n.s.			A = n.s.; B = 12.619; A/B = n.s.; B/A = n.s.		
Oligotrophic microorganisms (Ol) (10^6 cfu g^{-1})									
B1	65.0 ^a	40.0 ^a	52.6 ^a	51.0 ^a	34.0 ^a	42.5 ^a	37.3 ^a	64.0 ^a	50.7 ^a
B2	13.9 ^a	6.9 ^a	10.4 ^b	6.0 ^b	14.2 ^b	10.3 ^b	2.2 ^a	0.6 ^a	1.4 ^b
Mean	39.5	23.4		28.6	24.1		19.8	32.3	
LSD _{0.05}	A = 13.543; B = 13.543 A/B = n.s.; B/A = n.s.			A = n.s.; B = 9.224; A/B = 13.045; B/A = 13.045			A = n.s.; B = 14.400; A/B = n.s.; B/A = n.s.		

Abbreviations: see Table 3. ^{a,b}—letters in columns indicate significant differences at $p \leq 0.05$.

3.2. Chemical Analysis

Statistically significant differences were demonstrated for selected chemical parameters of soils between the summit and footslope of the hills, as well as between the genetic levels (Table 5). In terms of pH values, statistically lower pH values were observed at the footslope in two fields (S and T). Both TOC and TN contents indicated higher accumulation at the footslope, regardless of the genetic level. No statistically significant differences were noted in the content of available Mg; however, on fields R and S, Mg content was higher in the surface level at the summit, while for field T, the same trend was observed for TOC and TN. The content of available forms of K and P differed significantly between slope locations, irrespective of depth.

Table 5. pH level, TOC, TN, available Mg, P, and K content of the soil, depending on the soil profile and location on the slope.

Level of Factor B	Test Site R			Test Site S			Test Site T		
	Level of Factor A								
	A1	A2	Mean	A1	A2	Mean	A1	A2	Mean
pH value									
B1	6.33 ^a	7.14 ^a	6.73 ^a	8.18 ^b	6.48 ^a	7.33 ^a	8.36 ^b	7.01 ^a	7.66 ^a
B2	6.65 ^a	6.94 ^a	6.79 ^a	8.52 ^a	6.17 ^b	7.34 ^a	8.72 ^a	6.67 ^b	7.69 ^a
Mean	6.49	7.04		8.35	6.33		8.54	6.82	
LSD _{0.05}	A = 0.313; B = n.s. A/B = n.s.; B/A = n.s.			A = 0.233; B = n.s. A/B = 0.330; B/A = 0.330			A = 0.055; B = n.s. A/B = 0.077; B/A = 0.077		
Total Organic Carbon (TOC) ($g \cdot kg^{-1}$)									
B1	5.94 ^a	7.30 ^a	6.62 ^a	6.92 ^a	9.79 ^a	8.33 ^a	5.49 ^a	9.21 ^a	7.35 ^a
B2	2.85 ^b	6.38 ^b	4.62 ^b	2.71 ^b	8.25 ^b	5.48 ^b	3.94 ^b	5.90 ^b	4.92 ^b
Mean	4.40	6.84		4.82	8.99		4.72	7.56	
LSD _{0.05}	A = 0.117; B = 0.117; A/B = 0.165; B/A = 0.165			A = 1.055; B = 1.055; A/B = 1.492; B/A = 1.492			A = 0.233; B = 0.233; A/B = 0.329.; B/A = 0.329		

Table 5. Cont.

Level of Factor B	Test Site R			Test Site S			Test Site T		
	Level of Factor A								
	A1	A2	Mean	A1	A2	Mean	A1	A2	Mean
Total Nitrogen (TN) (g·kg ⁻¹)									
B1	0.69 ^a	0.71 ^a	0.70 ^a	1.05 ^a	1.10 ^a	1.08 ^a	0.81 ^a	0.90 ^a	0.86 ^a
B2	0.50 ^a	0.70 ^a	0.60 ^a	0.29 ^b	0.92 ^b	0.61 ^b	0.40 ^b	0.72 ^b	0.56 ^b
Mean	0.60	0.71		0.67	1.01		0.61	0.81	
LSD _{0.05}	A = n.s.; B = n.s.; A/B = n.s.; B/A = n.s.			A = 0.129; B = 0.129; A/B = 0.182; B/A = 0.182			A = 0.091; B = 0.091; A/B = 0.129; B/A = 0.129		
Magnesium (Mg) (mg·kg ⁻¹)									
B1	30.7 ^a	22.6 ^a	26.65 ^a	30.2 ^a	27.6 ^a	28.88 ^a	17.5 ^a	24.8 ^a	21.13 ^a
B2	41.1 ^a	19.8 ^a	30.45 ^a	21.00 ^a	29.4 ^a	25.18 ^a	29.4 ^a	30.2 ^a	29.78 ^a
Mean	35.90	21.20		25.55	29.40		23.45	27.45	
LSD _{0.05}	A = 11.851; B = n.s.; A/B = n.s.; B/A = n.s.			A = n.s.; B = n.s.; A/B = n.s.; B/A = n.s.			A = n.s.; B = n.s.; A/B = n.s.; B/A = n.s.		
Phosphorus (P) (mg·kg ⁻¹)									
B1	97.5 ^a	119.1 ^a	108.28 ^a	32.5 ^a	125.5 ^a	79.00 ^a	60.5 ^a	122.7 ^a	91.60 ^a
B2	51.7 ^b	94.9 ^b	73.28 ^b	21.5 ^a	98.9 ^a	54.68 ^b	31.1 ^b	111.3 ^b	71.20 ^b
Mean	74.58	106.98		21.48	112.20		45.80	117.00	
LSD _{0.05}	A = 9.908; B = 9.908; A/B = 14.012; B/A = 14.012			A = 10.175; B = 10.175; A/B = n.s.; B/A = n.s.			A = 6.276; B = 6.276; A/B = 8.875; B/A = 8.875		
Potassium (K) (mg·kg ⁻¹)									
B1	128.4 ^a	185.4 ^a	156.9 ^a	212.7 ^a	251.0 ^a	231.85 ^a	125.8 ^a	223.3 ^a	174.55 ^a
B2	117.5 ^a	101.2 ^b	109.4 ^b	116.3 ^a	142.8 ^a	129.55 ^b	85.7 ^b	221.1 ^a	153.40 ^b
Mean	122.93	143.30		164.50	196.90		105.75	222.20	
LSD _{0.05}	A = 13.381; B = 13.381; A/B = 18.923; B/A = 18.923			A = 20.524; B = 20.524; A/B = n.s.; B/A = n.s.			A = 11.377; B = 11.377; A/B = 16.090; B/A = 16.090		

Abbreviations: see Table 3. ^{a,b}—letters in columns indicate significant differences at $p \leq 0.05$.

3.3. TOC:TN Ratio and Granulometric Composition

The highest values of the TOC:TN ratio for locations R and T were observed in the surface level at the footslope, while for location S, they were found in the subsurface level at the summit. Similarly high values were noted in the subsurface profile at the footslope. The lowest values were recorded for the surface level (fields S and T) at the summit of the hill (Figure 3).

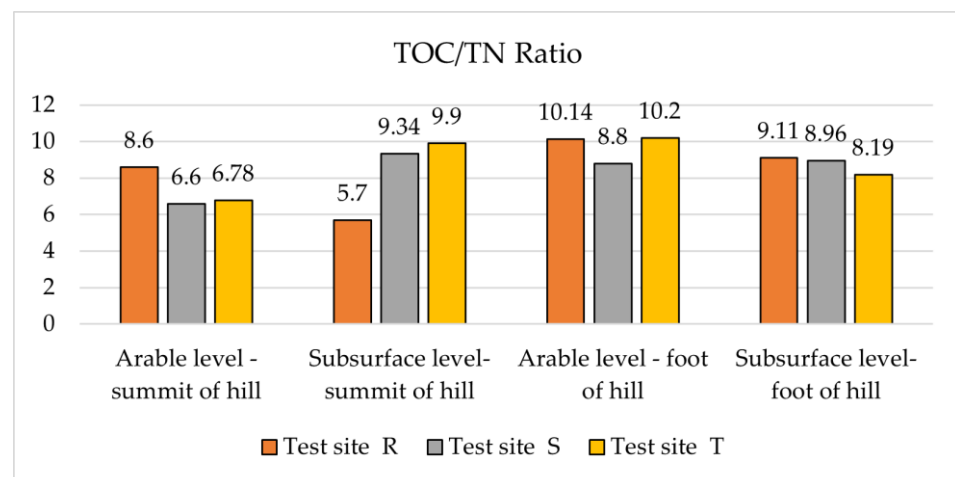


Figure 3. Carbon to nitrogen ratio values.

The particle size analysis revealed a higher proportion of sand in the surface level at the footslope, contrasting with the surface layer at the summit of the slope (Figure 4). The silt fraction, on the other hand, was higher in the surface and subsurface levels at the summit of the hill. Variations in the clay fraction were minor and did not exceed 6% in the composition of all examined samples. Nevertheless, higher values were also observed in the upper parts of the surveyed elevations.

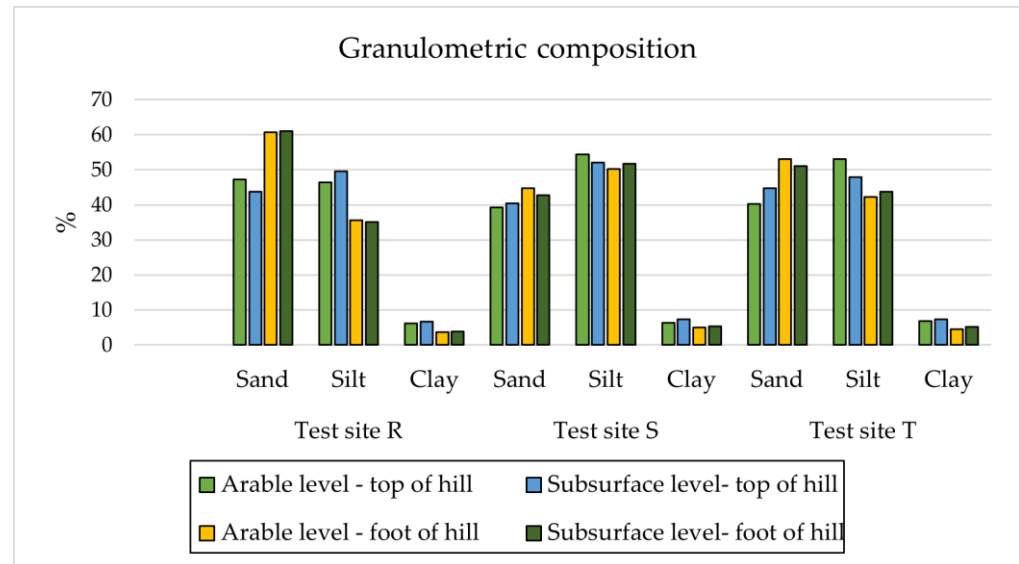


Figure 4. Particle size composition. Percentage content of sand (2.0–0.05 mm), silt (0.05–0.002 mm), clay (<0.002 mm).

3.4. Soil Electrical Conductivity

The surface layer of footslopes soil exhibited significantly lower average content of water-soluble forms of magnesium and calcium compared to summits (Table 6). However, in the soil material of the 0–30 cm layer of footslopes, a higher average content of water-soluble sodium was observed (Table 7). The average content of water-soluble potassium was lower in the surface layer of footslopes compared to summits. In the subsurface layer of the investigated footslope soils, a significantly higher average content of Na and Mg, and a significantly lower average content of Ca were recorded compared to summits. The highest content of water-soluble calcium cations was observed in the S and T subsurface horizons containing calcium carbonate.

Table 6. Sodium, potassium, magnesium, and calcium in the water-soluble fraction of surface soil horizon and values of soil electrical conductivity.

Location	Na	K	Mg	Ca	ECs
					$\mu\text{S}\cdot\text{cm}^{-1}$
					$\text{g}\cdot\text{kg}^{-1}$
R A1B1	6.6 ± 3.39	44.3 ± 1.27	15.9 ± 5.80	79.0 ± 1.84	93.4 ± 8.20
S A1B1	12.7 ± 4.17	77.9 ± 3.81	17.3 ± 1.27	201.0 ± 9.90	118.0 ± 3.68
T A1B1	8.7 ± 2.05	36.7 ± 0.92	16.4 ± 4.24	210.5 ± 2.12	166.9 ± 3.46
Mean	9.33	53.0	16.3	163.5	126.1
R A2B1	16.4 ± 4.38	38.3 ± 4.38	15.7 ± 1.63	40.8 ± 3.53	101.7 ± 1.34
S A2B1	11.1 ± 3.32	49.0 ± 1.63	13.7 ± 3.53	47.7 ± 3.61	148.6 ± 1.27
T A2B1	10.0 ± 0.35	21.2 ± 1.55	15.3 ± 0.56	33.4 ± 0.28	105.9 ± 0.78
Mean	12.5	36.2	14.0	40.6	118.7
	$p = 0.30$	$p = 0.32$	$p = 0.022 *$	$p = 0.045 *$	$p = 0.79$

Abbreviations: see Table 3; ECs—soil electrical conductivity, p —significance factor, *—statistically significant.

Table 7. Sodium, potassium, magnesium, and calcium in the water-soluble fraction of subsurface soil horizon and values of soil electrical conductivity.

Location	Na	K	Mg	Ca	ECs
	$\text{g}\cdot\text{kg}^{-1}$				$\mu\text{S}\cdot\text{cm}^{-1}$
R A1B2	9.5 ± 1.83	32.5 ± 1.55	11.6 ± 1.48	78.7 ± 4.10	70.2 ± 6.22
S A1B2	10.7 ± 2.19	40.5 ± 3.60	17.3 ± 2.33	240.5 ± 3.53	68.6 ± 7.71
T A1B2	10.6 ± 0,21	23.2 ± 0.99	13.6 ± 4.31	233.0 ± 2.12	159.3 ± 7.78
Mean	10.3	34.1	14.2	184.1	99.4
R A2B2	12.5 ± 0.85	42.7 ± 0.28	19.7 ± 1.77	32.8 ± 1.91	117.8 ± 6.64
S A2B2	12.3 ± 0.85	95.6 ± 0.56	22.5 ± 3.68	44.7 ± 1.77	148.5 ± 2.90
T A2B2	12.8 ± 0.71	41.5 ± 0.14	18.6 ± 3.82	32.6 ± 0.21	105.7 ± 4.38
Mean	12.5	59.9	20.3	36.7	124.0
	$p = 0.005 *$	$p = 0.21$	$p = 0.04 *$	$p = 0.49$	$p = 0.49$

Abbreviations: see Table 3; Table 6. *—statistically significant.

The soil material of the investigated areas did not exhibit salinity characteristics. In soil samples taken from the plow layer in summits, higher average values of ECs were recorded compared to footslopes. However, in the subsurface layer (B2), higher average values of EC were found in footslope soil. Tillage erosion processes did not significantly determine the values of soil electrical conductivity in the soil material on cultivated hillslopes.

3.5. Principal Component Analysis—PCA

Multivariate PCA (Figure 5) was employed to determine the nature and strength of correlations among the soil microbiological and chemical parameters studied (B, Ac, Ff, Co, Ce, Ol, pH, TOC, TN, available Mg, P, and K), hillslope location, and genetic level. Two principal components (PC1 and PC2) were extracted from the available data, explaining a total variance of 71.63%. PC1 accounted for the majority of the variance at 55.14%, while PC2 explained 16.49%. The PCA revealed that the first component (PC1) was significantly negatively associated with TOC (−0.823), TN (−0.751), and assimilated forms of K (−0.710) and P (−0.694). The second component, PC2, can be interpreted as describing microbial abundance, as it was significantly positively correlated with Ff, B, Co, Ac, Ol, and Ce.

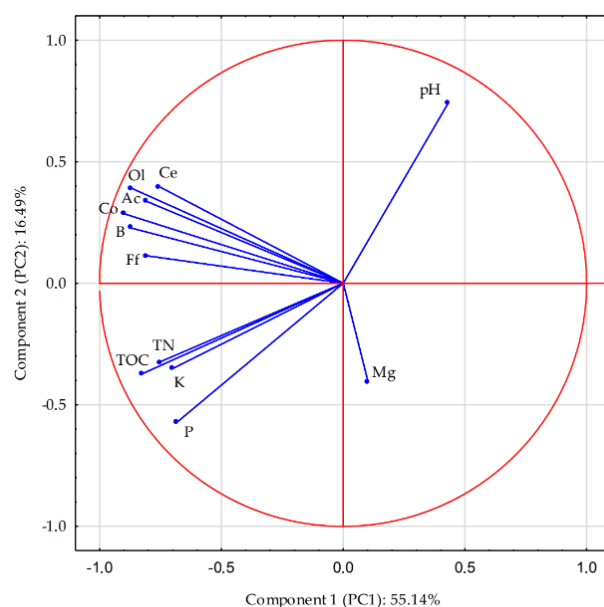


Figure 5. PCA—principal component analysis. PC1, PC2 of the studied soil microbiological properties (B, Ac, Ft, Ce, Co, Ol) and chemical properties (pH, TOC, TN, content of available P, K, and Mg). Abbreviations: see Tables 2 and 4.

The application of Cluster Analysis (CA) to the discussed parameters allowed for the determination of similarities (differences) between the sampling point's location and depth (Figure 6). Based on the dendrogram generated from the obtained data, three clusters were identified. Cluster 1, in the majority of cases (3 out of 5), grouped locations where soil samples were taken from the summit of the hills. These locations (RA1B1, RA1B2, and TA1B1) were characterized by a higher abundance of actinobacteria and the concentration of available phosphorus on the summit, compared to location S. Soil with the highest pH values and a lower overall bacterial count in the subsurface layer at the summit (locations SA1B2 and TA1B2) was grouped in Cluster 2. Cluster 3 distinguished 5 objects (RA2B1, TA2B1, SA2B1, TA2B2, SA1B1) where soil samples from the footslope were characterized by the highest content of TOC, TN, assimilated forms of P and K, and a higher abundance of selected microbial groups (Co, Ac).

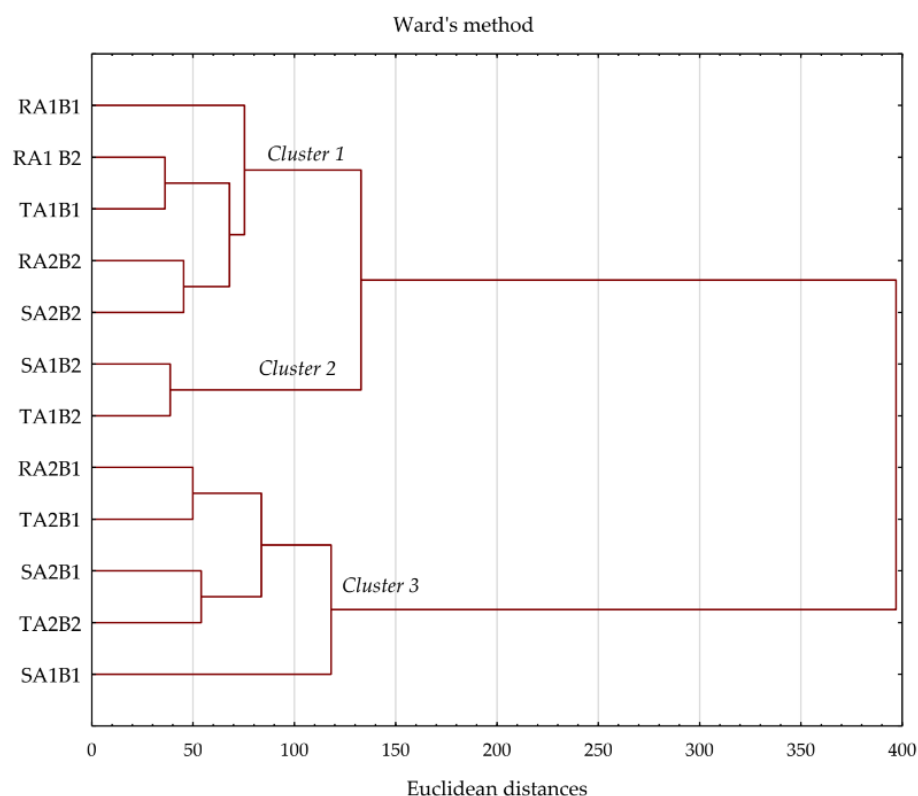


Figure 6. Dendrogram analysis of physicochemical and microbial soil characteristics. Abbreviations: see Table 3.

4. Discussion

Erosion and geomorphic processes are primarily associated with the impact of water, glaciers, and ice sheets on the Earth's surface. Currently, in the Anthropocene, the predominant geomorphic factor is the direct and indirect influence of human activities [39,40]. To date, the majority of studies on soil erosion have been dedicated to assessing changes in physicochemical parameters, with fewer focusing on the analysis of bacterial and fungal communities, as well as individual trophic groups. Addressing this gap in the literature has the potential to contribute to the formulation of a comprehensive approach for the early detection and prevention of anthropogenic erosion. In addition, this paper analyzes Luvisols, which, due to their widespread occurrence, impact food security and the stability of crop production [41,42].

In this study, all examined groups of microorganisms exhibited significant differences in abundance between the cultivation layer and the subsurface layer, regardless of the location on the eroded slope. This aligns with the scientific consensus, indicating that individual horizons should be treated as distinct ecological habitats [43]. The decrease

in the abundance of microorganisms along the depth gradient is influenced by several factors. Among the main factors is the increase in bulk density, which reduces the oxygen level, thereby limiting the developmental conditions for aerobic microorganisms [44]. Additionally, it is noteworthy that the arable layer contains more labile organic compounds, thereby promoting the development of heterotrophic microbiota. Another factor directly shaping the levels of microbial abundance is the impact of rainfall on the arable layer. Intense precipitation leads to soil moisture and the release of carbon from aggregates, contributing to increased availability of energy substrates [38,39].

The conducted research revealed variations in the microbial abundance in soil sampled from the summit compared to that at the foot of eroded slopes. While a significant increase in the overall bacterial count was observed in field T (LSD = 10.868), with a rise in count between the foot and summit in the plow layer by 666.77%, correlating with other reports [45–47], a similar phenomenon was not observed for oligotrophs and cellulolytic microorganisms. The higher level of oligotrophic abundance in the plow layer at the summit of the slope can be justified by lower carbon availability, creating an ecological niche for organisms with lower environmental requirements and enhancing the competitive advantage of this trophic group [48]. Although all soil samples were taken from post-wheat harvest sites, and changes in physicochemical parameters favored locations at the slope's base, cellulolytic microorganisms predominated at the summit. As highlighted by Huang et al. [49], sunlight intensity on the slope significantly influences microbial abundance, pointing to a relatively higher count of Gram-negative bacteria and aerobic microorganisms in shaded positions. The results obtained also revealed the prevalence of actinomycetes over the fungal population. This trend aligns with the evolutionary strategy of actinomycetes, as their capacity to metabolize a broad spectrum of hydrolytic enzymes and bioactive compounds enables them to exert fungistatic effects [50]. Furthermore, it has been demonstrated that the abundance of fungi in the soil is dependent on the use of organic fertilizers, which promote the proliferation of mycorrhizal fungi [51]. The soil pH is also of significance, indicating better environmental adaptation of fungi to lower pH levels [52]. In the case of our own research on two cultivation fields, the pH value at the hill's summit was alkaline and decreased to neutral with the depth of the soil samples. This trend may also indicate less favorable conditions for the development of fungi, as the optimal pH for their environment is slightly acidic.

All tested sites exhibited statistically significant differences in pH values, which increased with a decrease in elevation, confirming findings from previous studies [53]. The higher pH values, persisting at the summit on two sites, result from the presence of CaCO_3 , indicating a shallowing of the soil profile and mixing with calcium carbonate-rich bedrock [54]. Changes in organic carbon content are also a crucial indicator of advancing soil degradation, contributing to a reduction in soil productivity. The decrease in TOC content in the upper part of the hill aligns with the trend associated with the displacement of substrates along the elevation gradient. Moreover, as noted by Jia et al., the slope gradient plays a significant role in influencing changes in soil organic carbon content, particularly concerning water erosion [55]. The phenomenon of TOC transport, as a result of tillage erosion, leads to increased concentration at the deposition site at the foot of the hill, thereby hindering its decomposition and reducing bioavailability [56]. Observations regarding the dynamics of TN content levels on the slope are similar to the changes occurring in TOC. The connection between the redistribution of these two important elements has already been noted in previous studies [57,58]. Following a meta-analysis of 204 studies, Li et al. highlighted that the conversion of severely degraded fields into grassland contributes to enhancing the overall soil TOC and TN content, aligning with the principles of sustainable agricultural management [59].

It is worth noting that this trend also applies to the concentrations of assimilable forms of phosphorus and potassium. The presence of these elements is controlled by the amount of organic matter in the soil, which, due to precipitation and cultivation practices, moves along the slope gradient and accumulates at the foot. Subsequently, as a result of the

degradation of organic components by microorganisms, there is a release of elements and their reintegration into the nutrient cycle [53]. In the case of plant-available magnesium, no statistically significant changes were found in the levels of the altitude gradient, but it is noticeable that two fields showed higher levels of this element at the summit of the slope, which was also noted by other authors [60]. There is a possibility that, similar to the higher pH level at the summit of the hill, the element is released by the bedrock due to soil erosion.

Nutrients removed from cultivated fields along with plant yields must be adequately balanced by applied fertilizers. This is particularly important in precision agriculture, which focuses on improving the efficiency of agricultural production. Precision agriculture technologies allow for optimizing fertilization, the use of plant protection products, and the amount of fuel needed for cultivation operations [61,62]. This enables better utilization of agroecosystem capabilities, especially concerning non-renewable soil cover exposed to anthropogenic denudation.

5. Conclusions

In moraine areas subjected to intense agricultural anthropopression, the slope effect plays a significant role in shaping soil microbiota and changes in chemical parameters. The conducted research indicates a clear tendency to accumulate higher levels of organic carbon, total nitrogen, and plant-available forms of P and K at the foot of the slope, likely resulting from the transfer of soil material due to tillage and water erosion. Also, for most of the studied microbial groups, more stimulating conditions for their development were observed at the foot than at the summit, associated with the accumulation of larger quantities and easier access to nutritional substrates in these areas.

Microbial analysis indicates significant differences in microecosystems, depending on soil conditions and location. Variances in microbial composition between surface and depth, as well as among different locations, suggest the presence of specific microenvironments in the study area. These environments are strongly linked to the supply of nutrients and chemical elements, which are directly shaped by erosion processes. Recognizing the role of microorganisms could be a crucial aspect in better understanding, monitoring, and safeguarding biodiversity and the sustainable functioning of ecosystems. Monitoring microbiological and chemical changes in soil quality can be utilized as a prognostic tool to assess further erosive changes. Determining the impact of tillage erosion on the content of organic carbon and nitrogen, as well as shaping pH values and nutrient content in the soil is essential for targeted protection of agrocenosis.

The study found that over-intensification of agriculture negatively affects soil in moraine areas, leading to erosion. Cultivation operations move soil components from the tops of hills to the foothills. The findings underscore the need to adapt agricultural practices to the terrain, especially in hilly areas, and to use sustainable agriculture for long-term soil and environmental protection.

Managing the cultivation system and counteracting the effect of anthropogenic denudation is crucial both from an agricultural and environmental protection standpoint. By better understanding these processes and their consequences, one can contribute to the sustainable use of soil resources and the protection of agrocenosis.

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