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Effect of Soil Erosion on Soil and Plant Properties with a Consequence on Related Ecosystem Services

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Abstract: Erosion is a process often driven by land management deteriorating or changing soil properties along the slopes, with consequences on ecosystem services. In a model area with Stagnic Cambisol, with two different types of land use (grassland—GL and arable land—AL), on an erosion transect in three different hillslope positions (upper, middle, and lower), in two different depths (0–10 and 35–45 cm), we observed the impact of soil erosion on soil and plant properties and ecosystem services by use of direct measurements and models. In GL, soil available potassium (SK), soil available phosphorus (SP) and pH increased both downward along the slope and in soil depth. A significantly ($p < 0.01$) higher content of plant nutrients (PN, PP, and PK) and shoot biomass was recorded in the lower part of the hillslope. In AL, soil parameters (pH, SOC, SN, and SOC/SN) reached the lowest values at the middle hillslope position at the shallowest depth. A relatively negligible annual average soil loss was recorded for GL (0.76 t/ha/yr). To the contrary, a very high rate of soil erosion was found for AL with maize silage. The actual soil moisture was 50% higher in GL compared to AL, which was reflected also in the soil water deficit index (SWDI) being more favorable for GL.

Keywords: soil erosion; grassland; arable land; hillslope position; soil ecosystem service

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1. Introduction

Soil is a non-renewable and precious natural resource; it is crucial to sustainability and vital to human's existence. Soil is a fundamental part of the Earth's ecosystems [1]. It supports crop and animal production and plays a critical role in delivering many ecosystem services. Nevertheless, soils are jeopardized by a wide range of natural processes or human activities, such as long-lasting rainfalls or various forms of intensive land and agricultural use.

Erosion is a natural phenomenon caused by several factors, such as by the wind and especially by water [2]. It is thanks to erosion that some of the most fertile soils of plains and mountains and hilly landscapes have been formed [3]. On the other hand, erosion is accelerated by human activities such as agricultural activities and becomes unsustainable when soil loss exceeds its rate of formation [4].

Sustainable land use is a major challenge of current land management. Land degradation generated by soil erosion is one of the main issues within the Sustainable Development Goals adopted by the United Nations in 2015 [5]. Currently, soil erosion belongs to the most extended soil degradation process in the world [6]. Mountain structures result in high water erosion rates [7]. Intense rainfall and conventional tillage practices coupled with poor soil structure and steep slopes significantly accelerate soil erosion [8]. Soil water erosion is a complex process during which fertile topsoil is disrupted by water, transported away, and deposited on concave parts of slopes [9]. The result of water erosion process can be creation of colluvial soils on concave parts of slopes. The sediments can display various grain size distribution and diverse contents of soil organic matter, iron, and carbonates. In addition, pedoturbation intensifies a continuous mixture of organic and inorganic material [10].

Erosion causes the leaching of organic matter and nutrients, and the deterioration of water quality and drainage systems. The supply of macronutrients such as phosphorus, calcium, nitrogen, and carbon stocks are modulated by erosion [11]. Even slight erosion negatively affects farming conditions and yield [12] and leads to a loss of ecosystem services [13].

In this study, we are looking for an answer to the question of how soil erosion of differently managed lands can affect basic soil and plant properties with an impact on ecosystem services and their potential. The research was performed at a model area with Stagnic Cambisol, at two study sites (two slopes) with different types of land use (grassland and arable land), in the cadastral area Kečovo, eastern Slovakia, on an erosion transect in three different hillslope positions (upper, middle, and lower), in two different depths (0–10 and 35–45 cm). The main objectives of this study were (1) to evaluate the spatial and vertical differences in the soil's physical and chemical properties in three different hillslope positions (upper, middle, and lower), in two different depths (0–10 and 35–45 cm), and under two different land use management strategies, (2) to evaluate plant properties affected by water erosion, (3) to predict potential soil losses due to water erosion using an empirical model (Universal Soil Loss Equation—USLE) under two different land use management strategies, (4) to estimate the potential of soil ecosystem services (carbon stock, nitrogen stock, and water retention) under the influence of water erosion, and (5) to assess how the intensity of management, soil, and environmental factors affect water erosion's impact on soil and plant properties, reflected in ecosystem services' potential.

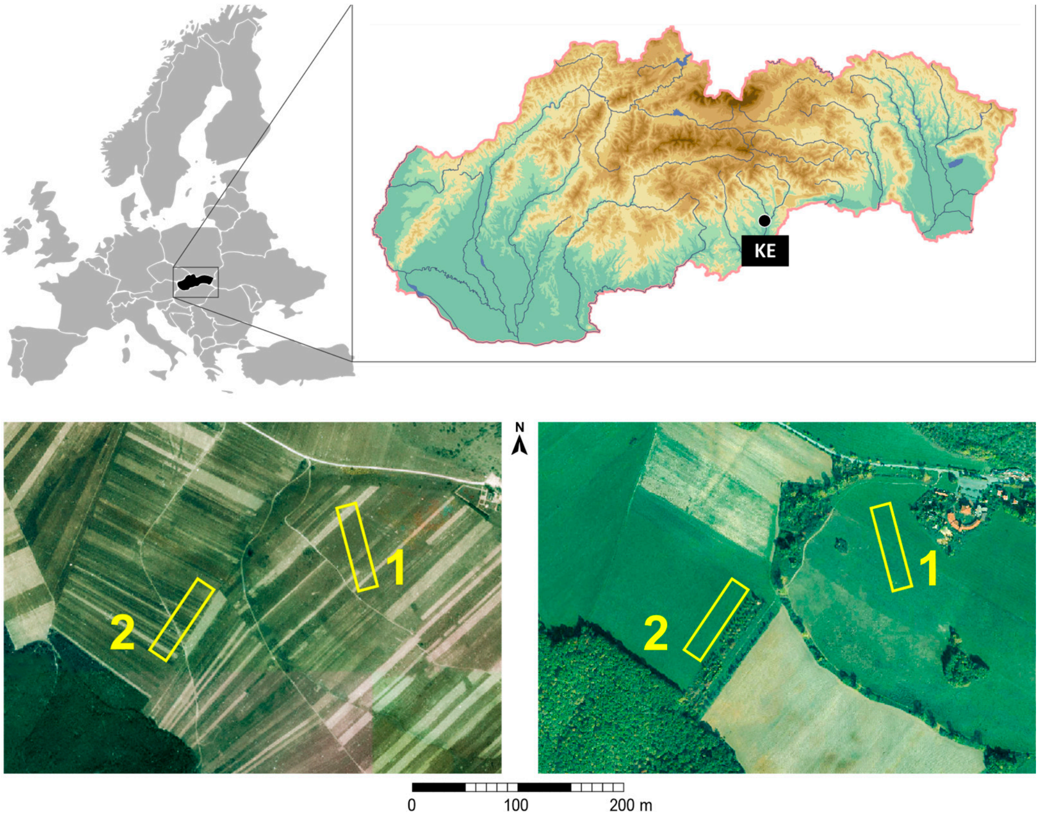
2. Materials and Methods

2.1. Sites Description

This study was conducted in Slovakia on two short steep (from 10 to 12%) slopes used as grassland (GL) and arable land (AL). Slovakia is mostly a mountain country (55% of the land territory) located in the western Carpathians. The climate is temperate. A high variability of soil types and soil particles over short distances is typical for some Slovak mountain and lowland regions as well [14]. In Slovakia, approximately 39% of agricultural land is threatened by water erosion [15]. The study area with two study sites was situated in the cadastral area Kečovo, located in the Slovak Karst region (part of the Silica plateau) in the Western Carpathians. The Slovak Karst spreads over more than 800 km^2 and its largest area is located between 500 and 700 m a.s.l. The terrain comprises medium height mountains. The altitude difference between the valley and the plateau surfaces is ~400 m [16]. From a geological perspective, the Slovak Karst is a complex of Mesozoic rocks/Wetterstein limestone [17].

The soil type at the study sites was classified according to the World Reference Base for Soil Resources [18] as Stagnic Cambisol (CMst) developed on slope neogenic sediments [19]. The long-term (30-year period) annual average total precipitation is 620 mm and annual average air temperature is 8.6 °C. On the arable land, a monoculture of silage maize was grown. The extensive permanent grassland was cut in June and grazed by suckler cows in the second half of the vegetation season.

At the study sites, strip farming has been the main cultivation practice, adopted since the High Middle Ages until the late 1950s. (Figure 1a). The fields of arable land were mainly oriented across the slope. After collectivization in 50s, the fields were merged into large blocks and thus exposed to the influence of erosion (Figure 1b). At present, study site 1 is used as grassland and study site 2 as arable land. The size of each selected plot was 7200 m^2 (with dimensions of 180 × 40 m). The GPS coordinates are 48°28′33.26″ N, 20°27′57.01″ E of study site no. 1 (center point), and 48°28′26.74″ N, 20°27′37.27″ E of study site no. 2 (center point).



(**a**) (**b**)

Figure 1. Study area location with two study sites (1, grassland and 2, arable land) and their aerial photographs in (**a**) 1953 (before collectivization) and (**b**) 2021. The historical orthophoto map was created within the project of the Center of Excellence for Support of Decision Making in Forest and Landscape, Technical University in Zvolen and is available at http://mapy.tuzvo.sk (accessed on 30 June 2024). Historical orthophoto map © GEODIS SLOVAKIA, s.r.o. and Historical LMS © Topographic Institute Banská Bystrica. Orthophoto map © EUROSENSE, s.r.o. and GEODIS SLOVAKIA, s.r.o.

2.2. Soil and Plant Sampling and Analysis

We collected soil samples from 0–10 cm and 35–45 cm depths, in order to distinguish soil layers more and less exposed to erosion, from four sampling points with a Z-shaped pattern on an erosion transect in the three different hillslope positions (upper, middle, and lower). The distance between the upper and middle position is 90 m, as is that between the middle and lower positions.

We determined basic soil physical properties in undisturbed soil samples 100 cm^3 in volume that were sampled from both depths using core extracting tubes (Eijkelkamp Equipment for Soil Research, Giesbeek, The Netherlands). The gravimetric method according to Novák [20] was performed to determine bulk density (BD). Particle density (PD) was measured by the pycnometer method according to Blake and Hartage [21]. Physical and hydro-physical properties were calculated by the following formulas:

Bulk density (BD) (Equation (1)),

$$BD = \frac{m_d}{V} \ (\mathrm{g\ cm^{-3}}) \quad (1)$$

where m_d is the mass of dry soil in g and V is the sample volume in the core-extracting tube in cm^3.

Particle density (PD) (Equation (2)),

$$PD = \frac{m_d}{m_w}\ (\text{g cm}^{-3}) \tag{2}$$

where m_d is the mass of dry soil in g and m_w is the mass of water expelled by soil in cm^3.

We conducted the particle size analysis by the pipette method using soil particle sedimentation. Particle size fractions (sand, silt, and clay) were classified according to the United States Department of Agriculture (USDA) system. Penetrometric resistance (PR) was measured directly in the terrain by a penetrologger (Eijkelkamp Equipment for Soil Research, The Netherlands). Soil moisture (SM) and soil temperature (ST) were measured using a WET sensor (Delta-T Devices LTD).

To estimate soil chemical properties, soil samples were air-dried and sifted through a 2 mm mesh sieve. Soil reaction was determined as pH in 1 M KCl solution (with a ratio of 1:2.5). Tjurin method (a modification of Nikitin) [22] was performed to determine soil organic carbon (SOC) content. Soil organic matter (SOM) was recalculated by 1.724 coefficient. Total soil nitrogen (SN) content was determined by the Kjeldahl method [23]. Soil plant-available nutrients K (SK) and P (SP) were extracted by Melich III [24]. SP was measured calorimetrically on the analyzer Scalar and SK by flame photometry. To distinguish soil and plant elements, we used the designation S for soil and P for plant nutrients.

In grasslands, plant samples were taken from the three different hillslope positions at the same sampling points as the soil samples. To assess the shoot dry matter yield, the grassland shoot biomass was clipped in May from twelve quadrats (each quadrat of 0.25 m^2) and oven dried at 60 °C to constant weight. The shoot biomass of maize silage was sampled in late September before harvest. The plant samples were taken from 1 m^2. Plants were cut and oven dried at 60 °C to constant weight. To estimate root biomass, soil cores (15 cm depth and 5 cm in diameter) were taken. Roots were extracted from the soil samples by washing in nylon bags and dried at 60 °C. The content of plant N (PN), P (PP), and K (PK) in shoot biomass was determined as follows: the PN content was analyzed by the Kjeldahl method [AOAC], the content of PP was determined colorimetrically by a continuous flow SNA, and the PK content was analyzed by flame photometry. The amount of carbon in shoot and root biomass was calculated by multiplying the biomass by the conversion factor 0.475 [25].

2.3. Soil Loss Rate Calculation

To assess the annual soil loss rate, we used the Universal Soil Loss Equation (USLE) [26] as follows (Equation (3)):

$$\text{A} = \text{R} \times \text{K} \times \text{LS} \times \text{C} \times \text{P} \tag{3}$$

where A is the estimated average soil loss ($\text{t.ha}^{-1}.\text{yr}^{-1}$), R represents the rainfall erosivity factor ($\text{MJ.mm}^{-1}\ \text{ha}^{-1}.\text{h}^{-1}.\text{yr}^{-1}$), K represents the soil erodibility factor (t.ha^{-1}), SL represents the slope-steepness factor, C represents the crop/vegetation factor, and the support practice is expressed by P.

Rainfall erosivity factor (R) is determined (Equation (4)) as a sum of a storm kinetic energy event, EI30, multiplied by its maximum 30 min intensity, I30.

$$\text{R} = \frac{1}{N}\sum_{1}^{N}(Etot\ I30) \tag{4}$$

where R [$\text{MJ.ha}^{-1}\text{cm.h}^{-1}$] is a rainfall erosivity factor averaged for a period of length, N. Onderka and Pecho [27] calculated the mean annual R-factor for 95 Slovak localities and determined the mean annual value of the R-factor for Slovakia as 711.3 $\text{MJ.ha}^{-1}\text{mmhr}^{-1}$.

Soil erodibility factor (K) reflects soil sensitivity to erosion, and it is a function of soil properties, particularly soil texture and soil organic carbon matter as well. Based on soil texture and SOM content, the values of the K factor, following McKague and Eng [22], ranged from 0.04 to 0.43 for average SOM content, from 0.05 to 0.41 for SOM content less than 2%, and from 0.01 to 0.37 for SOM content more than 2%. In our study, the GL soil has a clay–loamy texture and SOM ranged from 31.42 g.kg^{-1} to 48.62 g.kg^{-1}. The AL soil is loamy, and SOM ranged from 14.04 g.kg^{-1} to 23.27 g.kg^{-1}. Based on these data, we determined the K factor for GL as 0.28 and for AL as 0.41.

The slope length–gradient factor (LS) defines the influence of topography on soil erosion. It describes a ratio of loss of soil under concrete conditions to that at a site with the standard slope steepness of 9% and slope length of 22.13 m. The risk of erosion increases with the longer and steeper slope. In the Kečovo locality, the length and steepness of the GL and AL slopes were 150 m and 10%, respectively. To calculate the LS factor, we used the equation that follows (Equation (5)):

$$\mathrm{LS} = [0.065 + 0.0456\ (\mathrm{slope}) + 0.006541\ (\mathrm{slope})^2](\frac{slope\ lenght}{constant})^{\mathrm{NN}} \quad (5)$$

where LS is the slope length–gradient factor, slope is sloping steepness in %, slope length is in m, constant is 22.1, and NN values dependent on the slope are 0.2 for slopes steeper less than 1%, 0.3 for slope steepness that ranged from 1% to 2.9%, 0.4 for slope steepness that ranged from 3% to 4.9%, and 0.5 for slopes steeper than 5%.

The crop/vegetation factor (C) is a ratio of soil loss from land under a specific crop and management system. The C factor combines a specific crop type and tillage method. The values for crop types are as follows: grain maize—0.40, silage maize, beans—0.50, cereals (spring and winer)—0.35, seasonal horticultural crops—0.50, fruit tress—0.10, and hay and pasture—0.02. The following values were determined for various tillage methods: fall plot—1.00, spring plough—0.90, mulch tillage—0.60, ridge tillage—0.35, zone tillage—0.25, and no-till—0.25. In our study, for the C factor for GL, we multiplied the crop type 0.02 for hay and pasture and 0.25 for the no-till tillage method. For the C factor for AL, we used a 0.5 value for silage maize and 0.6 value for the mulch tillage system.

Support practice factor (P) describes the influence of agricultural practice that will reduce the rate of soil erosion. The P factor reflects the ratio of soil loss by a support agricultural method to that of straight farming down and up the slope. Following McKague and Eng, the support practice values have been established as up to down practice—1.00, cross slope—0.75, contour farming—0.50, strip cropping, cross slope—0.37 and strip cropping, contour—0.25. Because for AL, strip cropping and cross slope practices were applied, we used a P factor of 0.37. For GL, the P factor was 0.25, as strip cropping and contour practices were applied.

2.4. Estimation of Soil Ecosystem Services Using Models

Soil water retention hydrological ecosystem services (WRHES) capacity, soil carbon accumulation ecosystem services (SCAES), and soil nitrogen accumulation ecosystem services (SNAES) were estimated using different models. We used different calculation formulas introduced by Gupta and Larson [28] for temperate pedotransfer functions [29] as field water capacity (FWC), wilting point (WP), and available water capacity (AWC) to estimate WRHES.

Field water capacity (FWC) (Equation (6)):

$$\begin{aligned} FWC = {} & 0.003075 \times Sa + 0.005886 \times Si + 0.008039 \times Cl + 0.002208 \times SOM \\ & -0.01434 \times BD \end{aligned} \quad (6)$$

Wilting point (WP) (Equation (7)):

$$\begin{aligned} WP = {} & 0.000059 \times Sa + 0.001142 \times Si + 0.0005766 \times Cl + 0.002228 \times SOM \\ & +0.002671 \times BD \end{aligned} \quad (7)$$

where *Sa* is the percentages 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 bulk density.

Available water capacity (AWC) (Equation (8)):

$$AWC = FWC - WP\ (\%) \tag{8}$$

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

For the calculation of the soil water deficit index (SWDI) characterizing a drought event, the following formula was used (Equation (9)):

$$SWDI = \left(\frac{SMa - FWC}{AWC}\right) \times 10 \tag{9}$$

where *SMa* is actual soil moisture in %, *FWC* is field water capacity in %, and *AWC* is available water capacity in %. The SWDI was proposed by Martinez-Fernandez et al. [30]. We applied the SWDI as a proxy indicator to see differences between land use types and hillslope positions. The input data do not meet standard requirements (e.g., SMa assessment for one day only).

Higher values of SMa, FWC, WP, and AWC indicate higher soil water retention hydrological ecosystem services (WRHES) capacity. Positive SWDI values indicate that soils have excess water; when it equals zero, soil is in the field capacity of the water content (that is, without water deficit). Negative values mean soil drought, and the water deficit is absolute (wilting point) when the SWDI reaches ≤ -10 [31]. The SWDI in the range 0–−2 indicates a mild, −2–−5 moderate, −5–−10 severe, and $\leq$−10 extreme drought level.

To estimate SCAES and SNAES, SOC stock (SOCS) (t.ha^{-1}) and SN stock (SNS) (t.ha^{-1}) were calculated according to Tan [32] and Chen [33] (Equation (10)):

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

where SOCS is the SOC stock pool (t.ha^{-1}) of the evaluated soil profile, SOCi is SOC content (g.kg^{-1}), BDi is bulk density (g.cm^{-3}), Hi is the soil thickness (m), 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 SNS (t.ha^{-1})] (Equation (11)):

$$SNS = \sum_{i=1}^{n} SNi \times \mathrm{BDi} \times \mathrm{Hi} \times \left(1 - \frac{\mathrm{G}}{100}\right) \times 10^{-1} \tag{11}$$

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

2.5. Data Analysis

The data were analyzed by using the Pearson correlation coefficients and analysis of variance (ANOVA). The statistical analyses were computed using SPSS Statistics 28.

3. Results

3.1. Basic Soil Physical and Chemical Properties under Different Land Use, Hillslope Position, and Soil Depth

Table 1 presents basic soil physical properties in GL and AL at different hillslope positions and soil depths. In GL, the BD ranged from 1.41 (in the 0–10 cm depth at the lower hillslope position) to 1.55 g.cm^{-3} (in the 35–45 cm depth at the upper hillslope position). In AL, the BD ranged from 1.35 (in the 0–10 cm depth at the lower hillslope position) to 1.59 g.cm^{-3} (in the 0–10 cm depth at the middle hillslope position). At all three hillslope positions in GL, the higher BD values were recorded in the 35–45 cm depth. In contrary, at the upper and middle hillslope positions in AL, the higher BD values were recorded in the 0–10 cm depth. The PD ranged from 2.63 to 2.71 g.cm^{-3}. Soil texture was variable among the hillslope positions, depths, and land uses. Soil has a clay to clay–loamy texture in GL and a clay, loamy, and silty loamy texture in AL. In GL, fine clay fractions increased downward along the slope, and vice versa the sand fractions. On the contrary, in AL, coarse sand fractions increased downward along the slope, just like gravel. The SM values were always higher in the first soil layer and in GL. In the 0–10 cm soil depth, the lowest SM values were recorded in the upper hillslope position under both land uses. The highest SM value (40.8%) was recorded at the middle hillslope position in GL and at the lower hillslope position in AL (19.8%). Lower ST values were recorded in AL compared to GL.

Table 1. Soil physical properties.

Land Use	Hillslope Position	Soil Depth (cm)	BD ($g.cm^{-3}$)	PD ($g.cm^{-3}$)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	SM (%)	ST (°C)
Grassland	Upper	0–10	1.45 ± 0.05	2.69 ± 0.02	31.43 ± 2.36	24.15 ± 1.42	44.42 ± 3.50	2.3 ± 0.4	33.8 ± 6.06	14.5 ± 0.44
		35–45	1.55 ± 0.04	2.70 ± 0.01	39.58 ± 2.55	33.12 ± 2.21	27.30 ± 2.64	5.8 ± 1.0	19.3 ± 3.70	9.4 ± 0.48
	Middle	0–10	1.42 ± 0.02	2.70 ± 0.01	35.01 ± 1.26	23.11 ± 1.12	41.88 ± 0.92	5.9 ± 0.7	40.8 ± 2.28	13.8 ± 0.51
		35–45	1.48 ± 0.04	2.71 ± 0.01	40.56 ± 1.55	35.12 ± 1.07	24.32 ± 2.34	10.3 ± 0.5	23.8 ± 1.48	8.8 ± 0.45
	Lower	0–10	1.41 ± 0.02	2.70 ± 0.01	38.25 ± 1.75	28.14 ± 1.23	33.61 ± 1.71	5.7 ± 1.1	38.0 ± 1.87	15.0 ± 0.77
		35–45	1.52 ± 0.03	2.71 ± 0.01	43.78 ± 3.82	39.98 ± 1.38	16.24 ± 3.25	10.2 ± 0.5	21.0 ± 3.16	9.7 ± 0.13
Arable land	Upper	0–10	1.55 ± 0.11	2.64 ± 0.01	21.69 ± 3.88	54.98 ± 3.06	23.38 ± 4.69	5.1 ± 0.2	15.8 ± 1.15	10.9 ± 0.45
		35–45	1.51 ± 0.04	2.66 ± 0.01	46.23 ± 2.42	38.88 ± 1.73	14.89 ± 1.47	10.4 ± 0.5	9.0 ± 0.90	6.0 ± 0.25
	Middle	0–10	1.59 ± 0.05	2.65 ± 0.01	25.89 ± 2.43	47.95 ± 1.94	26.21 ± 2.67	20.3 ± 2.5	19.3 ± 1.17	10.4 ± 0.80
		35–45	1.58 ± 0.03	2.70 ± 0.03	48.97 ± 4.23	39.01 ± 3.61	12.02 ± 4.38	30.4 ± 3.1	11.8 ± 2.15	8.5 ± 0.55
	Lower	0–10	1.35 ± 0.06	2.63 ± 0.02	17.71 ± 2.78	53.15 ± 2.62	29.14 ± 3.44	30.5 ± 3.1	19.8 ± 1.78	9.9 ± 0.70
		35–45	1.53 ± 0.10	2.70 ± 0.09	16.78 ± 1.04	46.99 ± 1.01	36.23 ± 1.53	50.7 ± 3.9	14.8 ± 1.25	8.6 ± 0.40

BD—bulk density; PD—particle density; SM—soil moisture; ST—soil temperature.

Figure 2 presents penetration resistance (PR) with related penetration depths (D) in GL and AL at different hillslope positions. Significant differences were found among the hillslope positions and land uses with regard to PR and D.

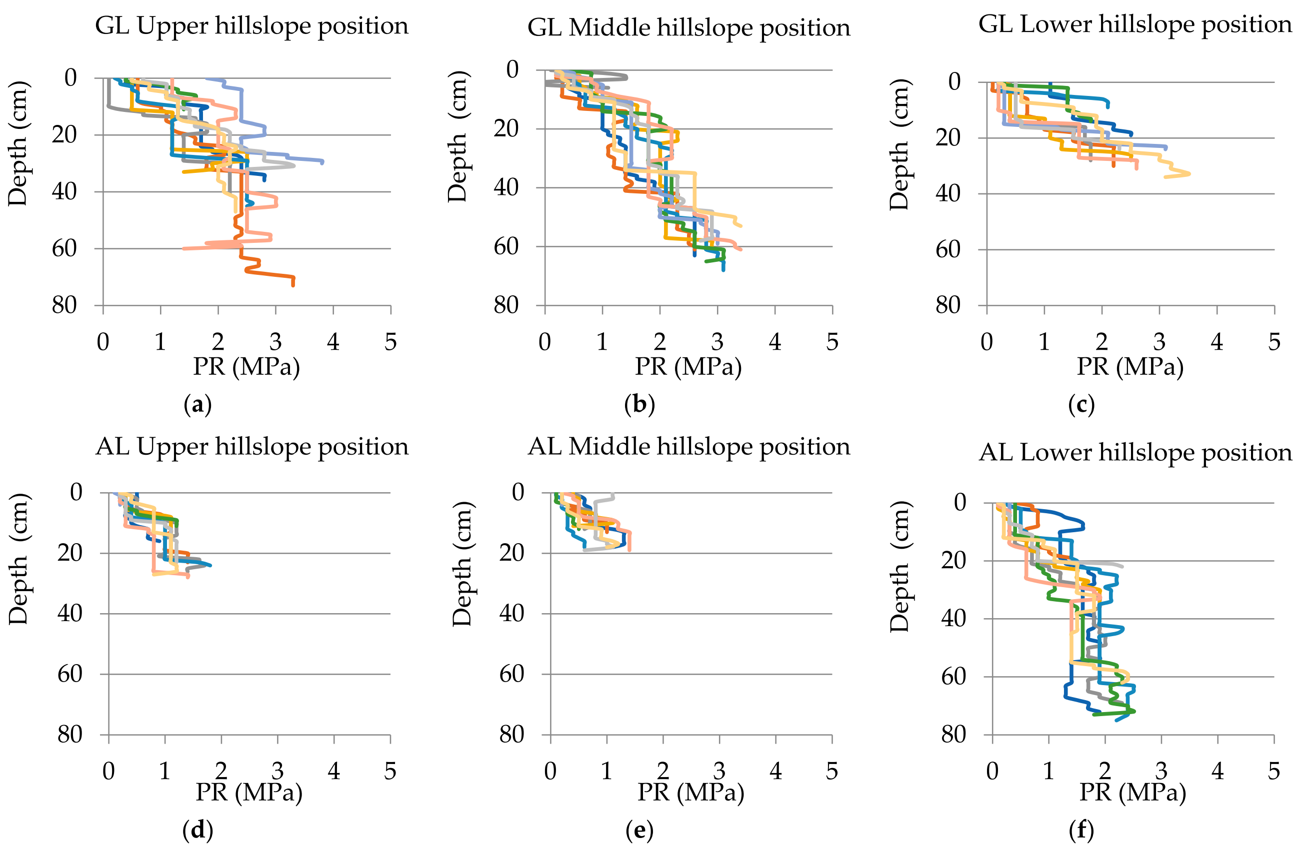


Figure 2. (**a**) Penetrometric resistance (PR) and penetration depth (D) in grassland (GL) at upper hillslope position; (**b**) at middle hillslope position; and (**c**) at lower hillslope position; (**d**) penetrometric resistance (PR) and penetration depth (D) in arable land (AL) at upper hillslope position; (**e**) at middle hillslope position; and (**f**) at lower hillslope position.

The mean PR for 20 cm depth ranged from 1.23 MPa at the upper hillslope position in GL to 0.67 MPa at the middle hillslope position in AL. The PR was significantly lower in AL compared to GL. In GL, the shallowest mean D (25 cm) was found at the lower hillslope position, and a much deeper mean D (42 cm) was measured at the upper and the deepest (60 cm) at the middle hillslope position, respectively. On contrary, in AL, the deepest mean D (52 cm) was found at the lower hillslope position as a consequence of accumulation processes which were reflected in the shallow mean D at the upper (24 cm) and middle (17 cm) hillslope positions.

Table 2 presents basic soil chemical properties in GL and AL at different hillslope positions and soil depths. In general, the soil reaction values ranged from weakly acidic, through acidic, to strongly acidic, from 4.78 to 5.93 in GL and from 4.85 to 5.54 in AL. The SOC content at the 0–10 cm depth ranged from 18.23 to 28.19 g.kg^{-1} in GL and from 8.15 to 13.50 g.kg^{-1} in AL. The SOC and SOM content was higher in the depth 0–10 cm compared to the 35–45 cm depth. However, the organic matter quality expressed by the SOC/SN ratio showed better quality in the 35–45 cm depth. The available SP content ranged from 0.15 to 22.83 mg.kg^{-1} in GL and from 4.33 to 24.91 in AL. The available SK content ranged from 84.40 to 349.3 mg.kg^{-1} in GL and from 130.75 to 221.93 in AL.

Table 2. Soil chemical properties.

Land Use	Hillslope Position	Soil Depth (cm)	pH	SOC (g.kg^{-1})	SOM (g.kg^{-1})	SN (g.kg^{-1})	SOC/SN	SP (mg.kg^{-1})	SK (mg.kg^{-1})
Grassland	Upper	0–10	5.04 ± 0.10	18.23 ± 2.81	31.42 ± 4.84	2.22 ± 0.29	8.21	0.15 ± 0.05	116.20 ± 5.31
		35–45	5.16 ± 0.07	6.98 ± 2.08	12.02 ± 3.59	1.19 ± 0.10	5.89	0.23 ± 0.08	84.40 ± 0.02
	Middle	0–10	5.14 ± 0.13	21.52 ± 2.98	37.09 ± 5.13	2.02 ± 0.20	10.66	1.28 ± 0.76	198.73 ± 47.02
		35–45	4.78 ± 0.28	7.25 ± 0.65	12.50 ± 1.12	1.05 ± 0.19	6.89	0.16 ± 0.03	99.84 ± 2.78
	Lower	0–10	5.89 ± 0.10	28.19 ± 2.10	48.62 ± 3.61	3.13 ± 0.29	9.01	22.83 ± 2.67	349.30 ± 3.50
		35–45	5.93 ± 0.15	24.15 ± 6.71	41.64 ± 11.58	2.75 ± 0.50	8.78	18.07 ± 8.50	321.33 ± 50.55
Arable land	Upper	0–10	5.22 ± 0.03	13.50 ± 3.31	23.27 ± 5.71	1.62 ± 0.09	8.33	24.91 ± 3.54	145.71 ± 20.67
		35–45	5.23 ± 0.07	13.05 ± 1.70	22.50 ± 2.93	1.58 ± 0.13	8.27	22.71 ± 2.50	130.75 ± 16.09
	Middle	0–10	4.85 ± 0.15	8.15 ± 0.77	14.04 ± 1.32	1.09 ± 0.10	7.47	5.12 ± 2.10	168.75 ± 29.79
		35–45	4.89 ± 0.12	7.73 ± 1.89	13.32 ± 3.27	1.04 ± 0.22	7.41	4.59 ± 3.41	179.65 ± 50.13
	Lower	0–10	5.46 ± 0.14	13.09 ± 3.00	22.56 ± 5.18	1.58 ± 0.09	8.31	4.84 ± 6.47	221.93 ± 86.20
		35–45	5.54 ± 0.08	8.63 ± 2.26	14.87 ± 3.90	1.42 ± 0.23	6.10	4.33 ± 6.70	182.87 ± 63.75

pH—soil reaction; SOC—soil organic carbon; SOM—soil organic matter; SN—soil total nitrogen; SP—soil plant-available phosphorus; SK—soil plant available potassium.

The values differed between hillslope positions and soil depths due to erosion–accumulation processes. The most significant accumulation processes at the lower hillslope position were manifested in the case of SK in GL as well as in AL. In GL, significant accumulation at the lower hillslope position was observed also in the case of SOC, SOM, SN, and SP. Overall, in PG, most chemical parameters (SK, SP, SOC, SOM, and pH) increased downward along the slope. In AL, most chemical parameters (pH, SOC, SOM, and SN) reached the lowest values at the middle hillslope position.

3.2. Grassland and Silage Maize Properties and Content of Nutrients with Different Hillslope Positions

Shoot biomass in GL ranged significantly among different hillslope positions, with the highest values in the lower part (223 g.m^{-2}) and the lowest in the middle parts of the hillslope positions (95 g.m^{-2}). The highest value of root biomass was recorded in the upper hillslope position (837 g.m^{-2}). Contrary to GL, the highest shoot biomass of maize (1445 g.m^{-2}) was obtained in the middle part of the hillslope, followed by the upper part and lower part (Table 3). On average, the root biomass in AL was 1.3 times lower than in GL, with the highest values in the upper part. R/S ratios were not related to hillslope position. In GL, the R/S ratio was largest in the middle hillslope part. Compared to GL, the largest R/S ratio in AL was observed in the upper part.

In GL, the content of macronutrients differed between hillslope positions (Table 4). In the lower part, the PN and PP concentrations were significantly higher ($p < 0.01$) compared to the upper part (Table 3). Grassland shoot biomass and PC/PN and PC/PP ratios decreased significantly downward along the slope with an increasing content of SN and

SP in the soil. To the contrary, an opposite trend was observed in AL, with the highest content of PN and PP and the lowest shoot PC/PN, PC/PP, and PN/PP ratios in the upper part, the lowest shoot PC/PN, PC/PP, and PN/PP ratios in the upper part. However, the content of macronutrients and PC/PN, PC/PP, PN/PP, and PN/PK ratios in maize did not exhibit significant change with the hillslope position.

Table 3. Shoot biomass, root biomass, and root biomass to shoot biomass ratio in grassland and maize grown on arable land.

	Hillslope Position	Shoot Biomass ($g.m^{-2}$)	Root Biomass ($g.m^{-2}$)	R/S
Grasslands	Upper	188 ± 88^{b}	837 ± 47^{ns}	5.23 ± 1.40^{ns}
	Middle	95 ± 35^{c}	663 ± 121^{ns}	6.57 ± 1.57^{ns}
	Lower	223 ± 59^{a}	611 ± 52^{ns}	2.61 ± 0.65^{ns}
	p value	0.009	0.179	0.107
Arable land	Upper	1186 ± 495^{ns}	340 ± 79^{a}	0.32 ± 0.14^{ns}
	Middle	1445 ± 448^{ns}	307 ± 24^{ab}	0.23 ± 0.08^{ns}
	Lower	1104 ± 593^{ns}	184 ± 45^{b}	0.21 ± 0.11^{ns}
	p value	0.826	0.003	0.171

Contrasting letters denote significant differences; ns—not significant, *p*—probability value.

Table 4. Content of macronutrients and PC/PN, PC/PP, PN/PP, and PN/PK ratios in grassland and maize grown on arable land.

	Hillslope Position	PN ($g.kg^{-1}$)	PP ($g.kg^{-1}$)	PK ($g.kg^{-1}$)	PC/PN	PC/PP	PN/PP	PN/PK
Grasslands	Upper	20.77 ± 1.16^{b}	2.97 ± 0.18^{b}	27.93 ± 3.10^{ns}	22.93 ± 1.29^{a}	160.41 ± 10.57^{a}	7.00 ± 0.40^{ns}	0.75 ± 0.11^{ns}
	Middle	21.56 ± 1.96^{b}	3.23 ± 0.21^{a}	22.43 ± 3.16^{ns}	22.20 ± 2.20^{a}	147.79 ± 10.92^{a}	6.68 ± 0.36^{ns}	0.97 ± 0.10^{ns}
	Lower	26.81 ± 2.60^{a}	4.02 ± 0.28^{a}	31.19 ± 3.28^{ns}	17.86 ± 1.65^{b}	118.56 ± 8.32^{b}	6.99 ± 0.36^{ns}	0.86 ± 0.06^{ns}
	p value	0.009	0.000	0.836	0.010	0.000	0.118	0.120
Arable land	Upper	14.66 ± 2.96^{ns}	4.38 ± 0.52^{ns}	7.64 ± 1.64^{ns}	33.68 ± 8.48^{ns}	109.61 ± 13.03^{b}	3.34 ± 0.57^{ns}	1.98 ± 0.62^{ns}
	Middle	13.66 ± 2.55^{ns}	3.44 ± 0.38^{ns}	9.83 ± 2.54^{ns}	35.74 ± 6.81^{ns}	139.07 ± 14.40^{a}	4.00 ± 0.97^{ns}	1.45 ± 0.34^{ns}
	Lower	11.81 ± 1.49^{ns}	3.45 ± 0.61^{ns}	7.71 ± 0.91^{ns}	40.71 ± 5.28^{ns}	141.35 ± 27.79^{a}	3.48 ± 0.51^{ns}	1.56 ± 0.32^{ns}
	p value	0.118	0.167	0.966	0.167	0.0472	0.804	0.213

PN—plant nitrogen; PP—plant phosphorous; PK—plant potassium; PC—plant carbon. Contrasting letters denote significant differences; ns—not significant, *p*—probability value.

3.3. *Relationships between Soil and Plant Properties*

The correlation coefficient matrix between soil and plant properties is presented in Table 5. The soil pH had a statistically significant positive relationship with other soil chemical properties, including plant nitrogen. The SOC had a significant positive correlation with all soil chemical properties, including two plant nutrients (PN and PK), and root biomass, while it had a significant negative correlation with shoot biomass, bulk density, and content of silt and gravel. For plant nutrients, the least numerous significant correlations with soil chemical and physical properties occurred in the case of PP. Soil physical properties affected mainly PK, ShB, and RoB.

3.4. *Annual Soil Loss by Water Erosion*

According to this study, the annual soil loss due to water erosion was strongly affected by land use. A negligible annual average soil loss was recorded for GL with permanent vegetation cover (0.76 $t.ha^{-1}.yr^{-1}$). To contrary, a very high rate of soil erosion was found for AL with maize silage (99.05 $t.ha^{-1}.yr^{-1}$). In the Slovak legislation [34], four soil severity classes are defined: low erosion severity (<4 $t.ha^{-1}.yr^{-1}$), moderate erosion (4–10 $t.ha^{-1}.yr^{-1}$), high erosion (10–30 $t.ha^{-1}.yr^{-1}$), and severe (>30 $t.ha^{-1}.yr^{-1}$). Based on the soil erosion severity category, the study site could be classified in the severe class.

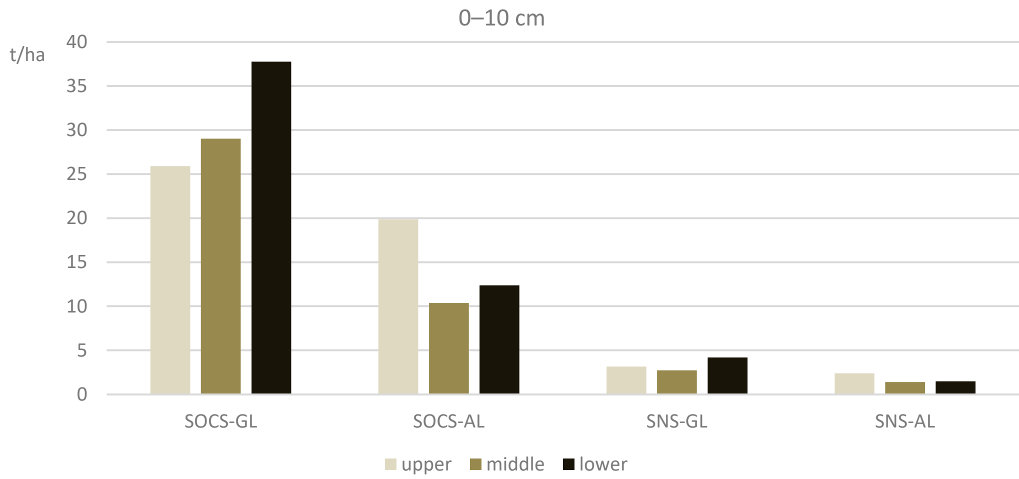
Table 5. Correlation coefficients among soil and plant properties.

	pH	**SOC**	**SN**	**SP**	**SK**	**PN**	**PP**	**PK**	**ShB**	**RoB**	**BD**	**PD**	**Clay**	**Silt**	**Sand**	**Gravel**
pH	1															
SOC	0.587 **	1														
SN	0.682 **	0.950 **	1													
SP	0.477 **	0.490 **	0.490 **	1												
SK	0.700 **	0.714 **	0.720 **	0.528 **	1											
PN	0.457 *	0.780 **	0.797 **	N.C.	N.C.	1										
PP	N.C.	N.C.	N.C.	0.559 **	N.C.	N.C.	1									
PK	N.C.	0.730 **	0.769 **	N.C.	N.C.	0.869 **	N.C.	1								
ShB	N.C.	−0.689 **	−0.646 **	N.C.	N.C.	−0.653 **	N.C.	−0.788 **	1							
RoB	N.C.	0.521 **	0.466 *	N.C.	N.C.	0.726 **	N.C.	0.804 **	−0.680 **	1						
BD	N.C.	−0.374 **	−0.376 **	N.C.	N.C.	N.C.	N.C.	N.C.	N.C.	N.C.	1					
PD	N.C.	N.C.	N.C.	N.C.	N.C.	N.C.	N.C.	0.442 *	−0.414 *	N.C.	N.C.	1				
Clay	N.C.	N.C.	N.C.	N.C.	N.C.	0.808 **	N.C.	0.828 **	−0.677 **	0.637 **	N.C.	N.C.	1			
Silt	N.C.	−0.397 **	−0.386 **	N.C.	N.C.	−0.765 **	0.411*	−0.874 **	0.789 **	−0.775 **	N.C.	−0.338 *	−0.535 **	1		
Sand	N.C.	N.C.	N.C.	−0.361*	N.C.	0.523 **	−0.530 **	0.684 **	−0.683 **	0.696 **	−0.435 **	N.C.	−0.524 **	−0.439 **	1	
Gravel	N.C.	−0.410 **	−0.378 **	N.C.	N.C.	−0.658 **	N.C.	−0.637 **	0.568 **	−0.656 **	N.C.	N.C.	−0.406 **	0.509 **	N.C.	1

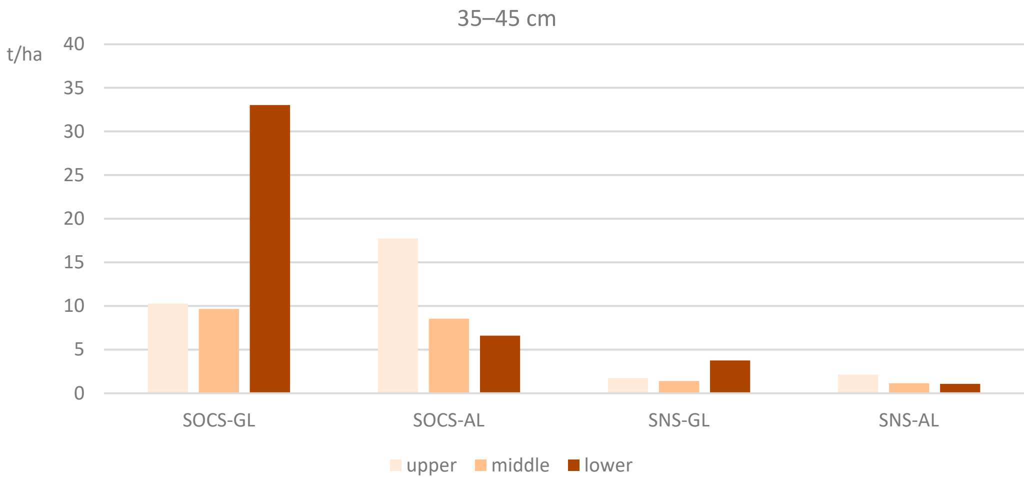
pH—soil reaction; SOC—soil organic carbon; SN—soil total nitrogen; SP—soil plant-available phosphorus; SK—soil plant available potassium; PN—plant nitrogen; PP—plant phosphorous; PK—plant potassium;, PC—plant carbon; ShB—shoot biomass; RoB—root biomass; BD—bulk density; PD—particle density; * r-values shown in bold are significant at $p < 0.05$; ** r-values shown in bold are significant at $p < 0.01$; N.C.—no correlation.

3.5. Potential of Soil Ecosystem Services Affected by Water Erosion

The impact of erosion–accumulation processes on soil properties was reflected in ecosystem services. Carbon and nitrogen stocks were influenced by hillslope positions, land use, and soil layer (Figure 3). Currently, the upper layer of soil is the most active in the ongoing carbon storage processes. However, deeper soil horizons also have a significant role in total carbon storage, which is obviously highlighted in the lower hillslope position in GL (SOCS 33.0 t.ha^{-1}). In GL, the SOCS for the top 10 cm layer ranged from 37.7 t.ha^{-1} in the lower hillslope position to 25.9 t.ha^{-1} in the upper hillslope position. The SOCS was significantly lower in AL, ranging from 19.9 t.ha^{-1} in the upper hillslope position to 10.4 t.ha^{-1} in the middle hillslope position. Similar trends were observed in the case of nitrogen stocks.



(**a**)



(**b**)

Figure 3. Soil organic carbon stock (SOCS) and soil total nitrogen stock (SNS) for 10 cm layers; (**a**) 0–10 cm depth; (**b**) 35–45 cm depth.

The effect of hillslope position, land use, and soil depth in the case of hydrological ecosystem services are obvious but not as pronounced as in the case of SOCS and SNS (Figure 4). The soil hydrological properties assessed by models using pedotransfer functions showed a much higher soil water retention potential in the case of WP in GL, and in the case of AWC in AL. However, the directly measured actual SM values were significantly higher in GL (37.5% as a mean value in the 0–10 cm depth) than in AL (18.3% as a mean value in the 0–10 cm depth), which was also reflected in the SWDI being more favorable for GL. The reason may be that the model does not consider the type of vegetation cover, which can contribute to increased water retention ecosystem services.

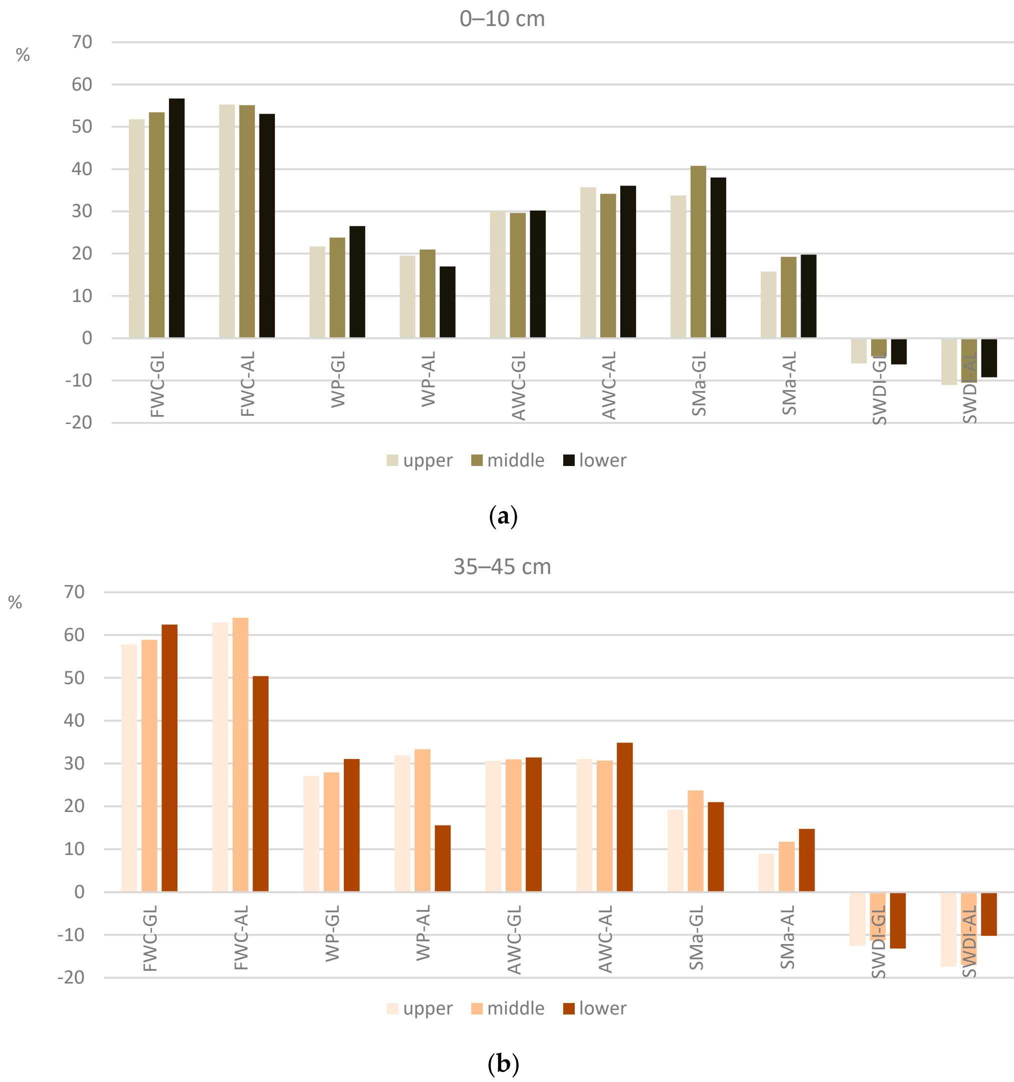


Figure 4. Field water capacity (FWC), wilting point (WP), available water capacity (AWC), actual soil moisture (SMa), soil water deficit index (SWDI); (**a**) 0–10 cm depth; (**b**) 35–45 cm depth.

4. Discussion

4.1. Soil and Plant Properties Affected by Water Erosion

We recorded a significant change in soil and plant properties in different hillslope positions, with an impact on the functioning of ecosystem services.

For the soil physical properties, significant changes along the slope were recorded in the values of penetrometric resistance as well as the depth of its measurement. Slope, pasturing, and type of vegetation strongly influence soil physical properties, including pentrometric resistance [35]. Soil resistance is one of the most dynamic properties of soil and it is important for plant growth and soil biological activities [36]. Lower PR at 20 cm was recorded in AL compared to GL as a consequence of ploughing. Better PR values in AL were in contrast to penetrometric depth, which was the shallowest (17 cm) at the middle hillslope position, where in GL, on the contrary, the greatest depth of penetrometric measurements was recorded (60 cm). The deepest penetrometric depth in AL was recorded at the lower hillslope position (52 cm) as a consequence of accumulation processes. This confirms how much impact erosion has on soil depth, which is largely corrected by vegetation and management. Erosion can reduce soil thickness and transport soil particles, and thus impact other soil properties, including water availability and thus soil hydrological ecosystem services [37].

Soil particles and their size and density are the main drivers of the transport and sedimentation process [38–40]. Previous studies showed that, as a rainy season lengthens, the eroded sediment particles become coarser and more stable [41]. Their distribution due to erosion along the slope was different between GL and AL. In AL, coarse sand fractions increased upward along the slope, just like gravel. On the contrary, in GL, fine clay fractions increased downward along the slope. Similarly, but in cropland, Liu et al. [42] recorded an elevated percentage of clay and silt content at the bottom slope position after soil redistribution was induced by erosion. Moreover, they also found mutual interactions between size fractions and SOC content. The high quantity of fine particles at the bottom-slope position was accompanied by an increase in SOC content, just like we noticed in GL.

The transport and loss of soil particles, together with weathering, have an impact on soil fertility [43] and nutrient (C, N, P, and K) supplies [44]. On the other hand, erosion can influence nutrient losses [45,46], and their spatial distribution. In GL, nutrients, such as SK and SP, increased downward along the slope, with the highest concentration at the lower hillslope position, together with SN. An increase of SN along a decreasing linear transect was shown in studies on eroded natural and artificial grasslands in China [47,48]. In AL, the content of SN reached the lowest values at the middle hillslope position with the shallowest depth. The content of SP and SK showed different variation. While the concentration of SK increased downward along the slope, the content of SP was 20% lower at the lower hillslope position compared to the upper position. This very low SP content could be caused by the very low downwards mobility of phosphorus [49]. The same tendency of a higher soil nutrient content in the lower part of the slope was also manifested in the highest content of PN, PP, and PK in shoot biomass for GL. Similarly, in AL, the highest content of soil SN and SP was reflected in the highest content in maize shoot biomass in the upper part of the slope. The soil nutrient redistribution with the water erosion also induced changes in plant nutrient dynamics and stoichiometry [50]. In our study, higher availability of SN was positively correlated with PN (r = 0.797**, $p < 0.01$) and PK (r = 0.769**, $p < 0.01$). Previous studies showed that a higher content of soil nutrients, particularly in grasslands [51], is associated with a higher content of PN, PP, and PK and lower shoot PC/PN and PC/PP ratios [52]. A higher availability of SN and a low PC/PN ratio results in decreased nitrogen use efficiency in terrestrial ecosystems [53]. The PN/PP and PN/PK ratios show how the ecosystem is limited by nitrogen, potassium, and phosphorus. As the PN/PP ratio was lower than 14 [54], and PN/PK was lower than 2.1 [55], the shoot biomass of grassland and silage maize were nitrogen limited in upper, middle, and lower hill positions as well.

4.2. Ecosystem Services Affected by Water Erosion

Soil properties condition the potential of ecosystems to provide services [56]. Therefore, to sustain the capacity to supply ecosystem services, soil protection is crucial [57]. The evaluated properties affect the potential of supporting, provisioning, and regulating ecosystem services.

Soil loss caused by erosion significantly disrupts soil formation processes as an important supporting service. In general, grasslands are more effective at controlling soil erosion than other vegetation covers. Because of a lower susceptibility to soil erosion [58], the maintenance of permanent grasslands and introducing temporary leys as green cover have been some of the priorities of Common Agricultural Policy since 2014 [59]. At our GL study site, annual average soil loss reached 0.76 t/ha/yr, which is a relatively negligible soil erosion rate without a major impact on soil ecosystem services [60]. To the contrary, AL with a silage maize cropping system showed extreme severe soil loss. Severe erosion on arable land in East Slovakia was shown by Koco et al. [61], who estimated soil loss of 18.1 t/ha for spring barley over a period of four months from March 2021 to July 2021 using remote sensing techniques.

Soil erosion is reported to have a significant effect on crop yield and thus on provisioning ecosystem services. In GL, a significantly lower shoot biomass was recorded in the middle hillslope position and in the shallowest soil depth compared to the lower position. Similarly, a study on the impact of temporary and permanent grasslands on slope stability in Lithuania [62] showed that grassland production in the southern exposition was the highest at the foot slope because of its more favorable soil moisture content. In AL, silage maize did not show a reduction rate of shoot biomass yield. These results contrast with a study from China where the mean maize seed yields decreased by 35% for severe erosion sites [63]. However, a European study on crop production showed that productivity in Northern Europe with current land use and soil loss is not significantly lowered due to water soil erosion. Nevertheless, in the Mediterranean region, yield reduction induced by soil erosion is stronger than in Northern Europe [64].

Soil erosion and spatial pattern conversion of land use results into the changes of regulating ecosystem services, such as carbon and nitrogen stocks or water-related ecosystem services [65], which we observed at our study sites. The soil hydrological properties displayed a much greater soil water retention potential in the case of WP in GL, and in the case of AWC in AL. However, the directly field-measured actual SM values were significantly higher in GL compared to AL. Grasslands are considered important in providing water retention as an ecosystem service [66]. However, GL degradation usually has an effect on the deterioration of soil hydraulic properties and, thus, soil water retention [67].

Globally, soils are considered as the largest terrestrial carbon reservoir, with a stock of approximately 2135 Gt SOC [68]. GL soils store about 10% of the global SOCS, which is nearly 50% more than in forest soils [69]. GL SOCSs are usually higher compared to AL SOCSs [70], as was confirmed by the results in our study, because of more plant-derived C inputs, mainly coming from root biomass and permanent cover [71]. In addition, the SOCS in AL is still being lost under current agricultural management [72], which is accelerated under erosion responsible for the degradation of physical and chemical soil properties. Our results showed the impact of erosion on C runoff, with subsequent redistribution of SOCSs within the soil profile under various land use. The land use and the intensity of management showed a difference in the SOC stocks as well as in their distribution at the different hillslope positions at the study sites. In GL, significantly higher SOC stocks were recorded compared to AL. However, in GL, we recorded the highest stocks and thus the accumulation of SOC at the lower hillslope position, in both monitored depths, with a greater emphasis in the second depth of 35–45 cm. In AL, we recorded the highest SOCS in the upper part of the slope, at a depth of 0–10 cm, and the lowest in the middle part of the slope. These variations in SOC reserves are a reflection of several linked biogeochemical processes taking place together with erosion processes and simultaneously influencing each other. In this way, the supply and distribution of nutrients in different parts of the slope are influenced, thus generating the formation of biomass as a prerequisite for SOC supplies. Carbon transfer as a result of erosion processes can control the global carbon cycle, with consequences on the ecosystem services and the evolution of the climate. Erosion induces a transfer of organic carbon from vegetation to river and sediments, and thereby acting to remove atmospheric CO_2 jointly with silicate weathering [7]. In our study, SOC was not transferred to a river, but was dominantly accumulated at the lower hillslope position. This presupposes the formation of colluvial soils. Soil type is a phenomenon as important as land use or other factors, having an impact on carbon stocks because of differences in geological material and the degree of its breakdown. Globally, large carbon stocks are in Cambisols, due to their vast area they cover [73]. Cambisols are relatively young soils with incipient subsoil formation connected with Fe oxides and clay mineral formation pedogenic processes. They predominantly accumulate organic matter in a top soil horizon. SOC content and then SOC stocks are further affected by other soil properties, as shown by correlation analyses.

Soil water erosion is a natural phenomenon and its negative impact on soil ecosystem services can be significantly reduced by sustainable land use and soil conservation management. The use of cover crops in areas with high soil erosion potential combined with limited soil disturbance technologies can partially or completely reduce the impact of climate change on soil losses [74]. Agri-environmental measures incorporated into the EU's Common Agricultural Policy (CAP) are considered to be the most efficient tool to stop soil degradation by erosion in the EU. Generally, more attention should be given to grasslands in erosion-regulating practices and ecosystem services. Much ecosystem services research is currently focused on forests and wetlands [75] or arable lands.

5. Conclusions

This study confirmed the effect of soil erosion on soil physical, chemical, and plant properties and related ecosystem services under different land uses.

The transfer of soil material from the upper and middle part of the slope and its accumulation in the lower part was evident and confirmed at AL by soil depth measurement, and sand particles increased downward along the slope. In contrast to AL, at GL, the shallowest profile was found at the lower hillslope position, and finest clay fractions increased downward along the slope. Overall, in PG, most soil chemical parameters (SK, SP, SOC, SOM, and pH) increased downward along the slope, where plant biomass and some plant nutrient concentrations (PN and PP) were also significantly higher compared to the upper part. However, in contrast, root biomass displayed the highest amount in the upper hillslope position. The content of macronutrients in maize did not exhibit significant changes with the hillslope position, probably due to fertilizer application. Correlation analysis showed the relations between soil and plant properties. A significant positive correlation was found between SOC and all soil chemical properties, including two plant nutrients (PN and PK), and root biomass. For plant nutrients, the least numerous significant correlations with soil chemical and physical properties occurred in the case of PP. Soil physical properties affected mainly PK, ShB, and RoB.

Soil and plant properties were reflected in ecosystem services. The study displayed that the annual soil loss by water erosion was strongly affected by land use. A relatively negligible annual average soil loss was recorded for GL. To the contrary, a very high rate of soil erosion was found for AL with maize silage. The upper layer of soil was the most active in the ongoing carbon storage processes. However, deeper soil horizons have also a significant role in total carbon storage, which was highlighted in the lower hillslope position in GL. The SOCS was significantly lower in AL compared to GL. Similar trends were observed in the case of nitrogen stocks. The differences in hydrological ecosystem services were not so pronounced between different land uses. The estimated soil hydrological properties showed a much higher soil water retention potential in the case of WP in GL and in the case of AWC in AL.

The results showed how serious changes are taking place in the soils affected by erosion, with consequences on plants and ecosystem services. Hilly and mountainous areas require even more careful and complex agricultural management than lowland areas, due to soil erosion problems. The conservation cropping systems for hills and mountains should be based on favoring permanent crops such as grasslands, the expansion of rotation, the use of cover crops, and the reduction of tillage. These interventions will have a significant effect on the agricultural ecosystems of Slovakia and of many European environments.

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