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INFLUENCE OF MORPHOMETRIC RELIEF PARAMETERS ON SOIL DEPTH CHANGES AND HUMUS HORIZON THICKNESS IN RELATION TO EROSION-ACCUMULATION PROCESSES: A STUDY IN THE IPEĽSKÁ PAHORKATINA HILLS, SLOVAKIA

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Abstract

Moravčík M., Petlušová V., Petluš P.: Influence of morphometric relief parameters on soil depth changes and humus horizon thickness in relation to erosion-accumulation processes: a study in the Ipeľská pahorkatina hills, Slovakia. Ekológia (Bratislava), Vol. 43, No. 1, p. 1–15, 2024.

This study examines the spatial distribution of soil types and their susceptibility to erosion and accumulation processes in a study area in Slovakia. Field research involving 71 probes identified various soil types, with Regosols and Cutanic Luvisols being predominant. The study found that erosion-accumulation processes were detected in 69.97% of the probes, with changes observed in soil horizons. Soil analysis revealed different relations between soil depth, humus thickness, and terrain characteristics such as slope, slope length, and slope length and steepness factor (LS factor). Specifically, we confirmed a moderately strong positive correlation between soil depth and humus thickness ($r = 0.597$, $n = 71$, $p < 0.001$). Shallow soils (0–30 cm) exhibited a very strong positive correlation between soil depth and humus horizon thickness ($r = 0.978$, $n = 33$, $p < 0.001$). Conversely, no relationship was found in moderately deep soils (30–60 cm) ($r = 0.018$, $n = 14$, $p < 0.948$). For deep soils, we identified a moderately strong positive correlation ($r = 0.345$, $n = 24$, $p = 0.098$). While slope and slope length showed relationships with soil depth and humus thickness, the LS factor did not exhibit a clear correlation. These findings underscore the importance of understanding soil dynamics in informing land management practices, especially in areas susceptible to erosion. Recommendations include continued monitoring of eroded soils and implementing erosion control measures to maintain soil health and sustainability in agricultural production amidst climate change challenges.

Key words: soil erosion, slope; slope length; potential soil loss; soil horizon thickness, total soil depth.

Introduction

Soil erosion has been identified as a major soil degradation process, leading to a threat to the environment (Panagos et al., 2016). Human activities and agricultural practices lead to acceleration of soil erosion processes in croplands (Poesen, 2018). Owing to erosion of the surface, significant amount of the fertile horizon of the soil is lost. The total soil depth changes. The severity of the changes can vary and depends primarily on the intensity of the erosion and the characteristics of the affected soil and parent material. They significantly affect soil properties and change the typical soil profile (Bakker et al., 2005; Tremboš, Minár, 2002). Soil depth refers to the vertical distance between the soil surface and the underlying bedrock or parent material. This characteristic is crucial for soil, as it determines the available soil volume for plant growth, development of plant root systems, their stability, water retention, aeration, temperature regulation, and nutrient cycling (Gömöryová, Pichler, 2015; Petlušová et al., 2018). Soil depth exhibits considerable variability influenced by factors such as the type of parent material, climate, topography, and vegetation cover. However, natural processes like soil erosion and human activities such as changes in land use and soil disturbance can also affect soil depth. In the Slovak Republic, significant challenges with soil erosion exist in croplands due to hilly terrains and the intensive use of arable land, which feature larger field sizes compared to European standards. Such conditions pose a higher risk of erosion and soil loss.

The changes in land use in the regions of Slovakia over the last few decades have significantly influenced the development of erosion processes. This outcome can be attributed to the country's history of agricultural collectivization (Boardman, Poesen, 2007; Devátý et al., 2019; Krasa et al., 2009; Van Rompaey et al., 2007). In the past, the characteristic structure of the country was shaped by human activity, comprising small narrow strips of fields oriented along the contour and slope lines (Špulerová et al., 2018). A significant change occurred in the 1950s when collectivization led to the transformation of the mosaic of small narrow fields into large-scale arable land (Muchová, Raškovič, 2020). Simultaneously, the alteration in the management system has expedited the development of erosion processes. According to research by Solín, Cebaceur (1998), collectivization led to a 40% rise in soil erosion in areas highly susceptible to such processes. The conversion of land use, deforestation, and the transformation into agricultural land, particularly in undulating terrains, have escalated the potential for soil erosion.

The average farm in Slovakia has 80 hectares of agricultural land, compared to the EU average of 16.1 hectares ("Farms and farmland in the European Union—Statistics," 2023). In the Slovak Republic, the soil risk assessment and soil protection strategy within good agricultural and environmental conditions (GAEC) is based on universal soil loss equation (USLE) modeling (Šúri et al., 2002).

The study focuses on water erosion processes observed in the lowland hills of Slovakia. Water erosion is the process by which water gradually wears away and transports soil, rocks, and other materials on the Earth's surface, especially on arable land. It is a natural process that occurs over an extended period and can be triggered by various factors such as morphometric parameters, climatic conditions, and land management practices. Human activities, particularly intensive agriculture on arable land, exacerbate this process. Water erosion significantly impacts the environment by altering soil properties, affecting food production, influencing drinking water quality, impacting ecosystem services, contributing to eutrophication, diminishing biodiversity, reducing carbon stocks, and causing mud floods (Boardman, Poesen, 2007; Lal, 2001; Panagos et al., 2016). This process is further accelerated by vast expanses of monocultures, which have limited capacity to retain water in the landscape and contribute to a decrease in landscape biodiversity. Consequently, this situation leads to a decline in the soil's production capacity (Petlušová et al., 2021a).

In Slovakia, soil protection is primarily coordinated through the common agricultural policy (CAP), particularly by adhering to the standards of GAEC, as mandated by the European Union ("Guidance and Tools for CAP (GTCAP) Home-Guidance and Tools for CAP (GTCAP)-EC Public Wiki", n.d.)one of the main water sources for semi-arid areas of China, has a local deposit caused by soil erosion during past decades. However, a lack of monitor stations prevents better estimation of soil erosion levels. Therefore, we try to estimate soil erosion in the Huangtuyaozi (HTYZ. The CAP has contributed to reducing soil erosion in Europe. However, the implementation of crucial CAP policies, such as nature-friendly agricultural technologies and climate-smart measures aimed at soil protection or water retention in the landscape, comes at a high cost.

Studies on agricultural conservation practices have demonstrated a substantial improvement in soil infiltration capacity. Consequently, there is a notable decrease in surface runoff and erosion (Arsenault, Bonn, 2005; Auerswald et al., 2003; Farhan, Nawaiseh, 2015; Maetens et al., 2012; Morgan, Nearing, 2011; Verstraeten et al., 2002)we chose a statistical evaluation which modelled erosion using the USLE method from the cropping statistics for 2056 districts in Bavaria (70 547 km2; 29.8% arable. Typical agricultural conservation practices include reduced/no-tillage, mulch cover/crop residues, cover crops, and reduced application of herbicides (Borrelli, Panagos, 2020; Petlušová et al., 2021b; Strudley et al., 2008). Comprehensive and effective soil erosion protection relies on understanding the conditions under which erosion transpires. Therefore, there is a need for more detailed research into the factors influencing its development.

The research aimed to monitor and evaluate the significance of selected environmental factors contributing to water erosion development in a heavily agriculturally exploited hilly region of Slovakia. Our focus was on observing changes in soil depth and the thickness of the humus horizon. In the context of the lowland hills of Slovakia, erosion-accumulation processes can be tracked through alterations in these soil parameters. Despite extensive knowledge, long-term research, and the use of simulation tools and environmental threat models, soil degradation remains a common phenomenon in the lowland hills of Slovakia. The study area, situated in the Sebechlebská pahorkatina hilly landscape, represented an intensely used agricultural region demonstrating manifestations of soil erosion.

The research aims to address the following question: What is the correlation between selected morphopositional characteristics of the terrain and the variations in soil depth and thickness of the humus horizon concerning erosion-accumulation processes?

Material and methods

Study area

The study site is situated in the southern part of Sebechlebská pahorkatina, a subregion of the Ipeľská pahorkatina, which is itself a geomorphological subdivision of the Podunajská pahorkatina. Positioned along the eastern edge of the Podunajská pahorkatina, it spans a strip of land between the valleys of the Hron and Štiavnica rivers, as well as the Ipeľská niva. The site is located in the cadastral territory of the town of Dudince (Krupina district, Banská Bystrica self-governing region). Tremboš, Minár (2002) classify the morphological-morphometric type of relief as moderately rugged. The average elevation of the site is 172 m above sea level (m a. s. l.). (Fig. 1). The dissected upland primarily comprises neogene sediments and pyroclastics, interspersed with mesozoic formations, fractured layers, and overlaid loess and loess clays. It is characterized by an erosional-sedimentary relief of lowland hills, exhibiting slightly differentiated morphostructures without aggregation (Tremboš, Minár, 2002). The area of interest is 34.34 ha and represents one coherent soil unit on a slope. Its upper part is a plateau and is the watershed boundary. It represents a separate contributing area. In terms of the climatic regions of Slovakia, the locality belongs to the warm, dry climatic region of the district of mild winter and lowland climate (Bochníček, 2015). The average annual temperature is 8–9 °C, the average annual precipitation is in the range of 550–600 mm, evapotranspiration is 650–700 mm (Bochníček, 2015; Lapin et al., 2002). The predominant soils are clay loam to clay loam with no skeleton to deep soils (Sobocká, 2000). According to bonited soil ecological units (BSEU) in the close area, there are soils Luvisols, Fluvisols, and Cambisols (Hraško et al. 1993; Sobocká, 2000). The main form of land use in this area is intensive agriculture, in the form of large-block arable land, ploughed along the gradient, in which the following crops have been cultivated over the last six years: oilseed rape (*Brassica napus* L.), wheat (*Triticum aestivum* L.), grain maize (*Zea mays* L.), and barley (*Hordeum vulgare* var. *distichum* L.).

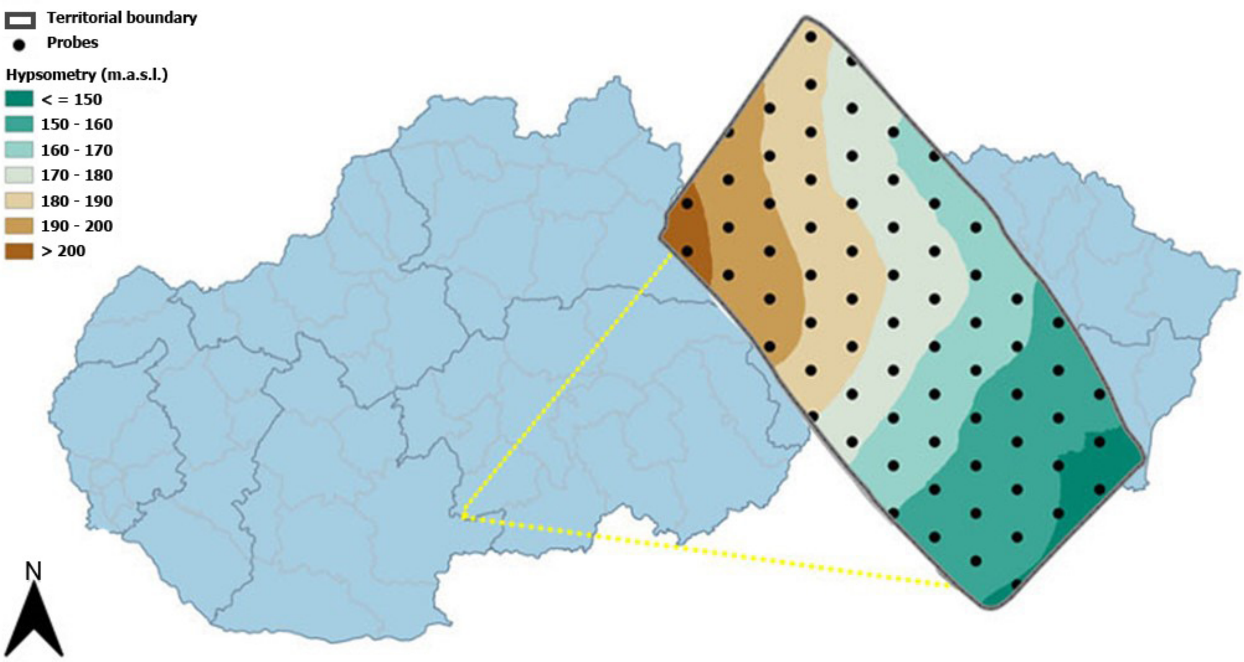

Fig. 1. Delineation of the territory within the administrative division of Slovakia.

Field survey

The significance of terrain research lies in comparing data acquired through erosion area modeling or visualization with the actual manifestation of erosion in the chosen area. We established a network of verification points with a resolution aligned to the arable land size, set at 75 m in our case. For verification purposes, we utilize the Edelman soil probe, as depicted in Fig. 2, capable of drilling up to 1200 mm in depth with a 50-mm diameter. Our assessment includes determining the presence of soil horizons, the thickness of the humus horizon, soil depth, parent material identification, as well as categorizing soil types and subtypes. Our field research for verifying eroded soils primarily focuses on heavily eroded soil areas that notably differ from the original noneroded soils due to the exposure of the lower section of the B or C horizon. These instances indicate the movement of soil particles from the upper section of the slope to the lower part.

Soil depth analysis

Soil depth is understood as the distance between the soil surface and the parent material (includes all identified soil horizons down to the parent material). Soil depth analysis was based on field research. According to Ilavská et al. (2005), Linkeš et al. (1996), soil depth was categorized into three primary types, as presented in Table 1.

Thinning of the soil layer occurs as one of the primary effects of water erosion on agricultural land, particularly evident in convex slope positions, while soil material accumulates in the depositional areas. In the convex slope positions, soil horizons are formed, with their upper layers significantly reduced (eroded) or even blended with the parent material. On the other hand,

Fig. 2. Edelman verification probe: Haplic Regosol (left); Cutanic Luvisol (right).

Table 1. Classification of soil depth according to Džatko, Sobocká (2009), in selected area.

Soil depth category	Soil depth [m]
Shallow soils	0–0.3 m
Medium-deep soils	0.3–0.6 m
Deep soils	>0.6 m

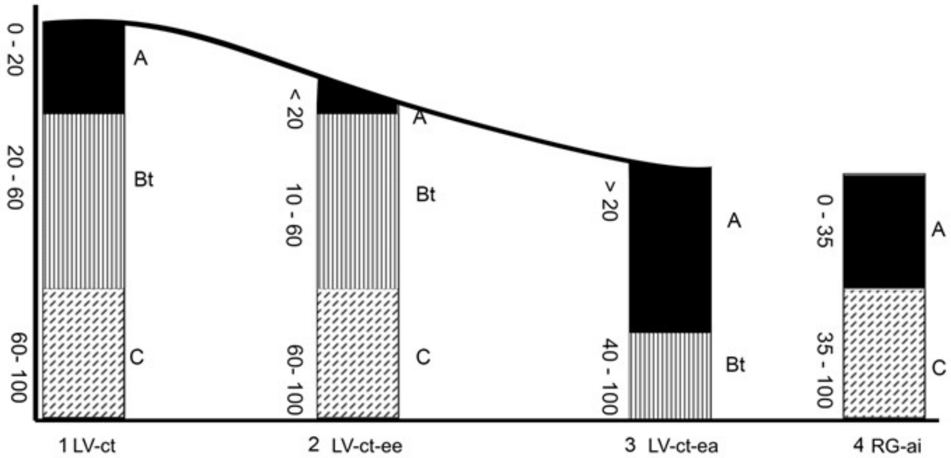

Fig. 3. Typical catena and changes in the arrangement of soil horizons on slopes in the study area as a result of erosion-accumulation processes. Notes: 1 – Cutanic Luvisols (LV-ct); 2 – Cutanic Luvisol eroded (LV-ct-ee); 3 – Cutanic Luvisol accumulated (LV-ct-ea); 4 – Regosols (RG-ai). Source: Sobocká, 2000.

deposition areas foster the formation of accumulated soils, characterized by a deeper A horizon.

Evaluation of erosion factors

This study assessed the significance of factors such as slope steepness, slope length, LS factor (a combined measurement of slope length and steepness) and potential annual soil loss. This framework has been utilized in the works of Wischmeier, Smith (1965), Morgan (2009), and Petlušová et al. (2016).

The key factors that affect soil erosion most significantly are slope and slope length. They are the most important features of the relief; they affect the speed and amount of surface drainage.

Slope serves as a fundamental morphometric indicator of terrain relief. We have established three slope categories: 1 (0°–3°), 2 (3°–6°), and 3 (>6°), which are edited by Ilavská et al. (2005).

Slope length refers to the horizontal distance from the initial point of surface runoff to the point where the slope becomes steeper, resulting in material deposition or concentration within the runoff path. It demonstrates the impact of continuous slope length relative to the size of soil drift and slope. The impact of slope length is observed in the erosion's severity, which escalates with the increment in slope length. It was classified into nine categories: 1 (0–200 m), 2 (200–400 m), 3 (400–600 m), and 4 (>600 m).

The LS factor, which combines slope length and slope, signifies the ratio of soil loss per unit slope area to soil loss per unit plot. It was classified into four adjusted categories (Petlušová et al., 2021b) relief shapes, aspect, slope length, combination slope length (L : 1 (0–1), 2 (1–5), and 3 (>5).

The potential annual soil loss was calculated according to the USLE equation (Wischmeier and Smith, 1965) in the following categories: 1 (0–4 t/ha/year), 2 (4–10 t/ha/year), 3 (10–30 t/ha/year), and 4 (>30 t/ha/year).

The analysis of factors was conducted within geographic information systems using a digital relief model DMR 5.0, adjusted to a 1-m resolution © ÚGKK SR. The calculation of factors was performed in the QGIS software environment utilizing the GRASS GIS modules.

The assessment involved comparing the soil depth and humus horizon thickness categories with the absolute value of the assessed factor. To quantify the correlation between soil properties and morphometric relief parameters, we utilized Pearson linear correlation analysis in PAleontological Statistics software (PAST).

Change in soil depth and thickness of the humus horizon and erosion factors

A significant indicator of change is the thickness of the humus horizon and the total soil depth. Changes can be observed along the gradient or catena. As the slope increases, the risk of soil particle transport also increases. Consequently, shallower soils occur on steeper slopes. In general, erosion intensity increases on straight slopes in proportion to slope length and gradient. Haplic Luvisol was chosen as the baseline soil type for the change assessment analysis (Džatko, Sobocká, 2009). The authors state that Haplic Luvisols are formed in the higher parts of hills (at elevations ranging from 150 to 450 m a s. l.). The substrate comprises eolithic decalcified sediments, mainly consisting of loess, loams, and polygenetic clays derived from old crusts of weathering neogene sediments. Currently, Haplic Luvisols are the most affected by erosion, primarily due to insufficient inputs of organic matter into the soil and deterioration of the soil structure. These are translocation soils, characterized by a dominantly Luvial Bt horizon beneath the usually ochric Ao horizon. The next represented soil type is Regosols. These are less developed soils resulting from an initial soil-forming process without other diagnostic horizons. In the conditions of Slovakia, their development is influenced by erosion processes. The individual soil profile thicknesses are shown in Fig. 3.

Results and discussion

Spatial identification of soil types

The spatial distribution of soil types was conducted through our field research, involving 71 probes. We identified various soil types, subtypes, and forms (Fig. 4). Predominantly, the study

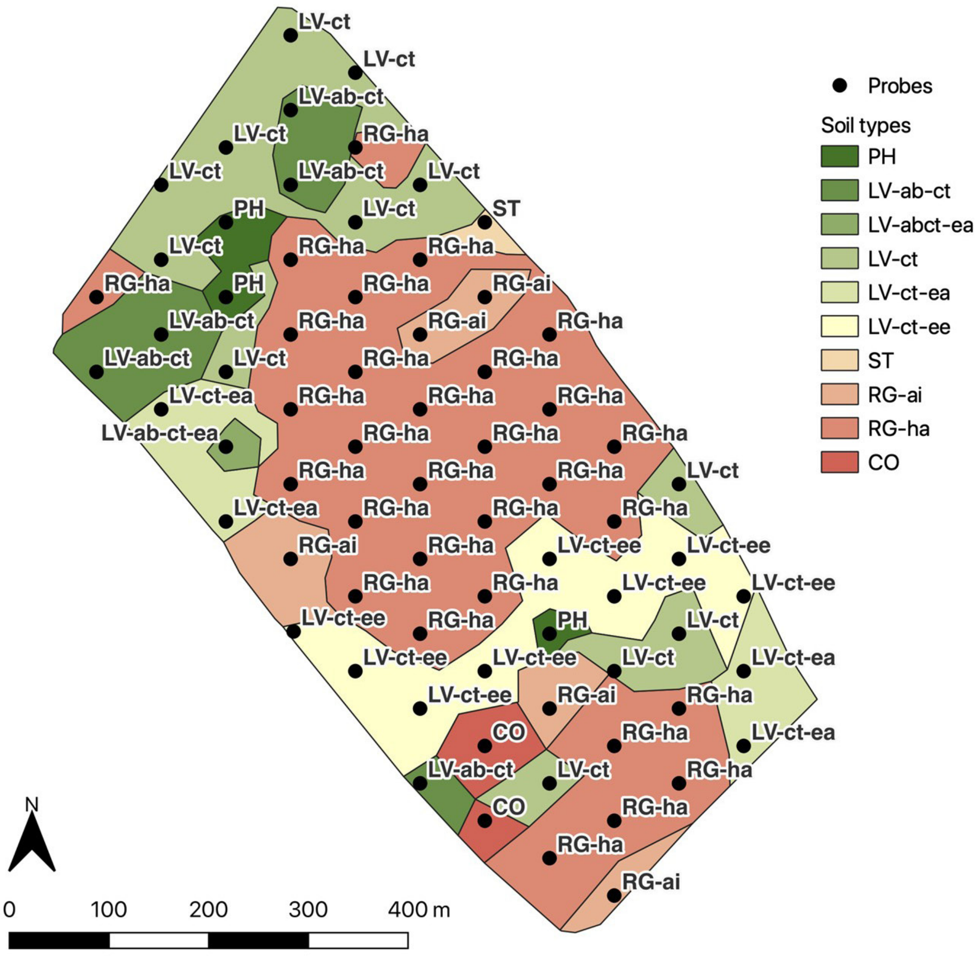

Fig. 4. Spatial distribution of soil types.

Table 2. Representation of soils identified through field surveys.

Soil type, subtype, form	Signature	Number of probes	Area [%]	Soil depth
Haplic Regosol	RG-ha	33	42.25	Shallow
Regosol aric	RG-ai	3	8.45	Medium-deep
Albic Cutanic Luvisol	LV-ab-ct	4	1.41	Deep
Cutanic Luvisol	LV-ct	5	8.45	Medium-deep
Cutanic Luvisol	LV-ct	7	11.27	Deep
Cutanic Luvisol accumulated	LV-ct-ea	6	5.63	Deep
Cutanic Luvisol eroded	LV-ct-ee	6	9.86	Medium-deep
Albic Cutanic Luvisol accumulated	LV-ab-ct-ea	1	1.41	Deep
Haplic Stagnosol	ST-ha	1	4,22	Deep
Haplic Phaeozem	PH-ha	3	4.23	Deep
Colluviosol	CO	2	2.82	Deep
Total		71	100.00	

area exhibited two primary soil types: Regosols (52.83%) and Cutanic Luvisols (41.45%), along with their respective subtypes and forms (Table 2). However, the resulting spatial soil cover may show significantly more variability in areas where the geological structure of parent materials is more complex or due to periodic shifts in climate and land use (Chodorowski et al. 2019; Khitrov et al., 2019) which most often showed graining of clay dust. Organic carbon content in humus levels did not exceed 2.9%. The surface levels of the analyzed molds showed clear decalcification. The $CaCO_3$ content in the loess mother rock was a maximum of

15.5%. These are soils with high saturation of the sorption complex with basic cations. The content of available phosphorus and potassium in humus levels was low and medium. According to Systematics of Poland's soils (2019). At the study site, Regosols were identified as shallow eroded soils. Additionally, both eroded and accumulated forms were observed in the Cutanic Luvisol. According to the research of Radziuk, Świtoniak (2022), it is evident that these soil types are highly vulnerable to erosion and accumulation processes. Regosols are often categorized as weakly developed soils. Despite their limited soil profile development, they are known for their potentially high productivity (Drewnik, Żyła, 2019). This observation also pertains to the area in question, correlating with the steepness of the slopes and the agricultural utilization of hilly land in Slovakia. It is recommended to monitor soils that exhibit strong erosion, particularly where the lower part of the Bt horizon and the C horizon are exposed, significantly darker than the A horizon or the upper part of the Bt horizon. This darker appearance is attributed to the considerably darker neogene sediments prevalent in our conditions.

Soil depth analysis

Out of a total of 71 probes in the area, erosion-accumulation processes were detected in 49 (69.97%) probes. Changes in the humus horizon strength were observed in the mapped soils displaying erosional processes. Vanwalleghem et al. (2017) and Yanda (2000) observed changes in soil horizons in relation to erosion-accumulation processes, utilizing reference marks such as the argillic B horizon to track these changes. This may reflect on the properties of the original and eroded soils. This was confirmed by the research of Bílá et al. (2020) and Świtoniak, (2014). Their analysis results and subsequent statistical evaluation showed that the chemical characteristics, particularly those associated with the quantity and quality of organic matter, were the most sensitive to changes in soil properties. It has been confirmed that eroded soils are typically located in the convex parts of the slope, while accumulated soils are found in the concave areas, foothills, and flat portions of the slope. Similar changes were also observed by Labaz et al. (2022), Zádorová, Penížek (2018). They documented the sequence of chernozemic and nonchernozemic soils (Chernozems, Phaeozems, and Calcisols) affected by water erosion due to intensive arable land use, and these changes were spatially dependent on the intensity of relief. In this context, Izakovičová et al. (2018, 2019) recommend that the principles of integrated landscape management should be used in planning the use of agricultural land. For example, proposal for a new land parceling reduction of arable land parcel size, preference for small-scale parcels, fragmentation of the arable land. Proposal for a change in the management of the agricultural land fund regarding the needs of nature protection, as well as measures for the proper exploitation of soils. Soils situated in elevated and highly inclined areas, subjected to intense erosion, experienced the loss of their mollic horizons and exhibited features resembling Calcisols. According to the soil depth categorization by Linkeš et al. (1996), within the selected area deeper soils (>0.6 m) are noticeable in the northwestern part of the slope, particularly on a gentle plateau (24 probes). Conversely, shallow, eroded soils (0–0.3 m) are predominantly located in the central area with the steepest slope (33 probes). In the southern part of the area, the slope decreases, and soil accumulation is evident, with medium-depth soils (0.3–0.6 m), totaling 14 probes (Fig. 5). In soils with an original A horizon thickness of 10-15 cm, plowing mixes it with underlying horizons, making it challenging to discern the original sequence and thickness of the horizons. Świtoniak (2014) estimated the influence of accelerated erosion on soil cover transformation in young morainic landscapes in northeastern Poland. He found that the average values of soil reduction are approximately 40 to 50 cm, and in the case of completely eroded soils, it even exceeds 100 cm. The extensive impact of intensive slope processes results in the widespread occurrence of thick (up to 3 m) colluvial deposits.

The shallow soil category (33 soil probes) exhibits an average soil depth of 23.79 cm and an average humus horizon thickness of 23.79 cm, represented by the soil type Haplic Regosol. In the medium-deep soils category (14 soil probes), the average soil depth measures 47.5 cm with an average humus horizon thickness of 30.71 cm. Soil types in this category include Regosol Aric, Albic-Cutanic Luvisol, Cutanic Luvisol, and eroded Cutanic Luvisol. The deep soils category (24 soil probes) showcases an average soil depth of 91.25 cm and an average humus horizon thickness of 48.13 cm. Soil types represented here encompass Albic-Cutanic Luvisol, Cutanic Luvisol, accumulated Cutanic Luvisol, accumulated Albic-Cutanic Luvisol, Molic Fluvisol, and Phaeozem (Table 3).

Changes in the morphology of soil profiles were detected at the monitored site, including variations in horizon thickness, absence of certain horizons, and alterations in the sequence of horizons within individual soil depth categories. These observed changes suggest the occurrence of erosion-accumulation processes (Smólczyński, Orzechowski, 2010; Świtoniak, 2014). The most significant changes are observed within the shallow soil category, predominantly characterized by Regosols with a truncated or absent A horizon. The soil depth corresponds to the soil horizon thickness (Fig. 6). Soil type represent A–C morphology with no other diagnostic horizon than an ochric, plowed surface horizon. This minimal development permits the classification of these soils only as Regosols. The formation of weakly developed Regosols as a result of truncation of former Luvisols has already been confirmed by Klimowic, Uziak (2001) in undulating areas of the Lublin Upland. The category of medium-deep soils is represented by Cutanic Luvisols, serving as the reference type in the study area for assessing the extent of arable soil transformation due to erosion. Luvisols developed from loess deposits were interpreted as reference pedons, crucial in understanding human-induced soil erosion in western Slovakia (Dotterweich et al., 2013). In the category of eroded Cutanic Luvisols, erosion predominates. Soil loss estimates were determined based on the depth to the lower boundary of a B horizon. A change in soil depth has been identified, related to the truncation of both A and B horizons. The presence of a few well-preserved Luvisols also enabled the estimation of several soil loss classes in the loess landscape in Saxony (Wolf, Faust, 2013). The variance in solum thickness of Alfisols and Mollisols was used as an indicator of the degree of erosion in north-central United States (Mokma et al., 1996). The category of deep soils mainly comprises Cutanic Luvisols, accumulated Cutanic Luvisols, and Colluviosol.

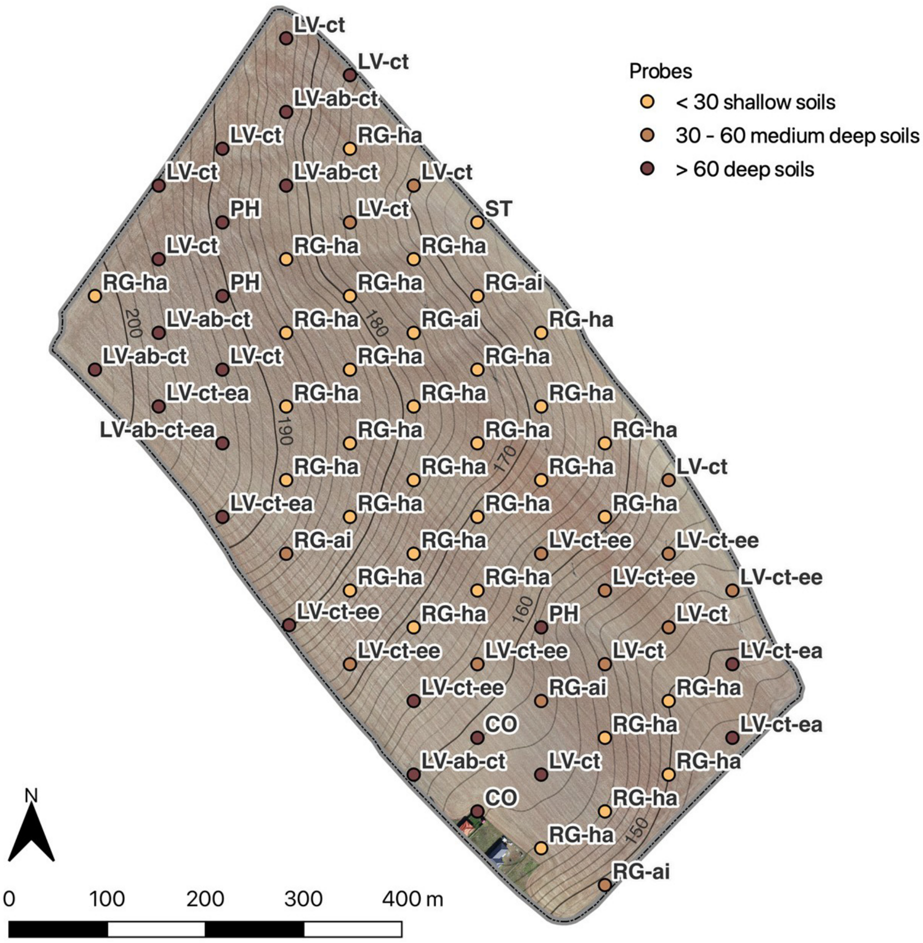

Fig. 5. Spatial distribution of soil depth and identified soil types.

Table 3. Statistical evaluation of soil depth in relation to the categories of total soil depth and humus horizon thickness (1 – shallow soils; 2 – medium-deep soils; 3 – deep soils; a – total soil depth; b – humus horizon thickness).

	1a	1b	2a	2b	3a	3b
	33	33	14	14	24	24
Min.	10	10	35	25	65	20
Max.	30	30	60	45	120	120
Mean	23.79	23.79	47.50	30.71	91.25	48.13
Std. error	0.72	0.72	2.39	1.72	3.53	6.07
Stand. Dev	4.15	4.15	8.93	6.46	17.27	29.74
Median	25.00	25.00	45.00	25.00	80.00	35.00

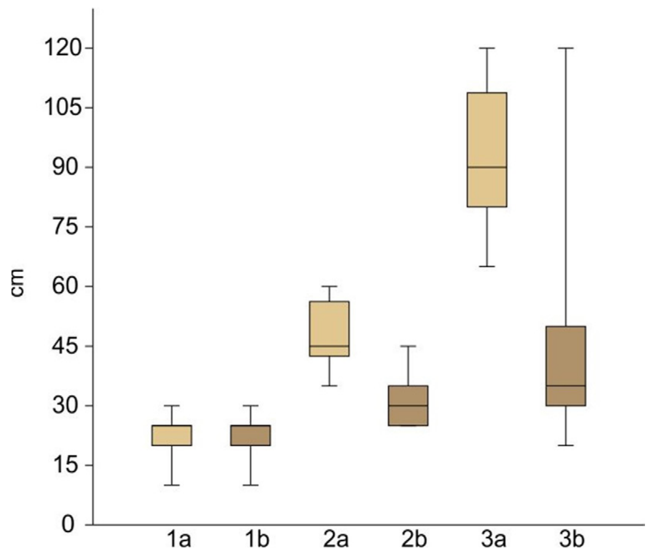

Fig. 6. Total soil depth and humus horizon thickness divided by soil depth category (1 – shallow soils; 2 – medium-deep soils; 3 – deep soils; a – total soil depth; b – humus horizon thickness).

This accumulated material is typically found on the backslope or in slope depressions where material deposition takes place. Świtoniak (2014) shows that the extent and thickness of colluvial soils depend on inclination, length and shape of slopes, and type of cultivation. In most cases, the thickness of colluvial

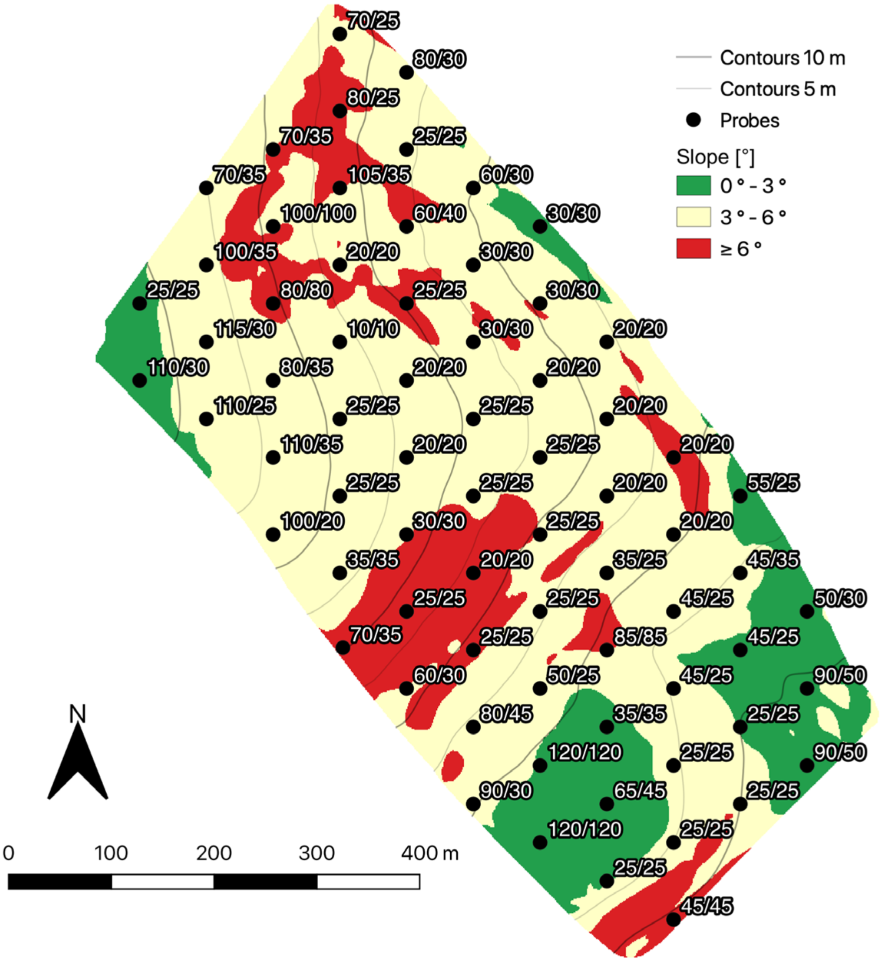

Fig. 7. The slope of the area and the total soil depth/the humus horizon thickness.

deposits was between 50 and 150 cm in northeastern Poland. In our case, the thickness of the humus horizon in the deep-soil category is 20–120 cm (mean 47.7 cm). The colluvial deposits are important for the interpretation of erosion (Baužienė et al., 2008; Twardy, 2011)soil erosion and water protection. Deluvial soils are part of national soil classification systems of Poland and until 1999 of Lithuania. In Poland, deluvial soils are one of two orders within the fifth division – alluvial and deluvial soils. Later (Mažvila ir kt., 2003; 2006.

We confirmed a moderately strong positive correlation between soil depth and humus thickness (r = 0.597, n = 71, p < 0.001). Consequently, total soil depth is positively associated with humus horizon thickness, increasing with greater soil depth (Gabbasova et al., 2016; Świtoniak, 2014). However, when analyzing correlations within specific soil depth categories, we discovered significant differences. Shallow soils (0–30 cm) exhibited a very strong positive correlation between soil depth and humus horizon thickness (r = 0.978, n = 33, p < 0.001). Conversely, no relationship was found in moderately deep soils (30–60 cm) (r = 0.018, n = 14, p < 0.948). For deep soils, we identified a moderately strong positive correlation (r = 0.345, n = 24, p = 0.098).

Erosion factors analysis and soil depth

Slope

The slope was categorized into three groups (Fig. 7), with the majority of the area falling into category 2 (3°–6°), covering 22.69 hectares (66.07%). Category 1 (0°–3°) was represented on 5.73 ha (16.67%), while category 3 (>6°) covered 5.73 ha (17.26%). The impact of the slope was particularly noticeable in the northeast section of the area classified under the 2nd category. Following extended periods of rainfall, gully erosion formed on the arable land in this region.

In the categories of slope, we analyzed the total soil depth and the humus horizon thickness. In the category of slope 0 -3° (mean 1.94°, n = 14), the soil depth was in the range of 25-120 cm (mean 63.21 cm). Cutanic Luvisols were mainly represented, less Regosols. Colluviosols in the colluvial part of the slope were represented, too. It was also confirmed by Mitusov et al. (2013). They report that deposition zones of colluvium occur in the lower concave slope sections and bottoms of depressions. Zádorová et al. (2023) states that colluvial soils occurs at the concave slope elements especially in landscapes with undulating relief often

Table 4. The complex statistical evaluation (1 – shallow soils; 2 – medium-deep soils; 3 – deep soils; a – total soil depth; b – humus horizon thickness).

Slope [°]	**1a** [0–3]	**1b** [0–3]	**2a** [3–6]	**2b** [3–6]	**3a** [>6]	**3b** [>6]
N	14	14	45	45	12	12
Min	25	25	10	10	20	20
Max	120	120	115	100	105	85
Mean	63.21	45.36	46.78	28.44	54.17	37.92
Std. Error	9.64	8.79	4.59	1.88	8.85	6.38
Stand. Dev.	36.09	32.90	30.77	12.61	30.66	22.10
Median	52.50	30.00	30.00	25.00	57.50	30.00

Slope length [m]	**1a** [0–200]	**1b** [0–200]	**2a** [200–400]	**2b** [200–400]	**3a** [400–600]	**3b** [400–600]	**4a** [>600]	**4b** [>600]
N	8	8	22	22	26	26	15	15
Min	25	25	10	10	20	20	25	25
Max	115	80	105	100	120	120	120	120
Mean	91.25	36.87	42.72	30.22	46.15	32.30	51.33	38.00
Std. Error	10.63	6.33	6.33	3.65	5.60	4.30	7.42	6.41
Stand. Dev	30.08	17.91	29.71	17.14	28.57	21.96	28.75	24.84
Median	105.00	32.50	27.50	25.00	32.50	25.00	45.00	25.00

LS factor	**1a** [0–1]	**1b** [0–1]	**2a** [1–5]	**2b** [1–5]	**3a** [>5]	**3b** [>5]
N	7	7	41	41	23	23
Min	25	25	20	20	10	10
Max	120	120	115	50	120	120
Mean	65.71	44.28	48.17	27.80	52.39	40.00
Std. error	13.68	12.88	4.85	1.10	6.82	5.91
Stand. dev	36.22	34.08	31.05	7.07	32.74	28.36
Median	55.00	30.00	30.00	25.00	45.00	30.00

Potential soil loss [t/ha/year]	**1a** [0–4]	**1b** [0–4]	**2a** [4–10]	**2b** [4–10]	**3a** [10–30]	**3b** [10–30]	**4a** [>30]	**4b** [>30]
N	11	11	24	24	35	35	1	1
Min	25	25	20	20	10	10	25	20
Max	120	120	120	120	105	100	25	20
Mean	66,36	40,45	53,96	32,08	44,43	31,86	25,00	20,00
Std. error	10,66	8,35	7,32	4,06	4,63	3,22	0,00	0,00
Stand. dev	35,36	27,70	35,84	19,89	27,38	19,02	0,00	0,00
Median	55	30	30	27,5	30	25	25	20

changed by long-term agricultural management. The thickness of the humus horizon of Colluviosols also varied from 25 to 120 cm (mean 45.36 cm) (Table 4, Fig. 8). In the slope category of 3°–6° (mean 4.93°, n = 45), the soil depth ranged from 10 to 115 cm (mean 46.78 cm). This category was characterized by the representation of Regosols, Cutanic Luvisols, and eroded Cutanic Luvisols. The humus horizon thickness varied between 10 and 100 cm (mean 28.44 cm). For the slope category exceeding 6° (mean 6.73°, n = 12), the soil depth ranged from 20 to 105 cm (mean 54.17 cm). Here, Regosols, mainly eroded Cutanic Luvisols, and Phaeozems were represented. Regosols and Cutanic Luvisols with an eroded form point to the presence of erosion processes in the upper (convex) slope sections. This was also confirmed by Drewnik, Żyła (2019) and Michno (2004) on the Proszowicka Plain, where they found that significant slope areas were also eroded, especially the upper (convex) slope sections. The humus horizon thickness varied from 20 to 85 cm (mean 37.91 cm). The higher average values of total soil depth and humus horizon thickness were attributed to the presence of Phaeozems. In Central Europe, these soils are considered azonal and are also found on slopes with higher degrees of inclination in terrain depressions. Here, these soils develop on fine-grained substrates that are unsuitable for rainwater infiltration (Rejšek, Vácha, 2018). The presence of Phaeozems on the slopes is also reported by Životić et al. (2017). These soils are characterized by the presence of a robust humus horizon, which, in our conditions, aligned with the total soil depth. Across all soil depth categories, we observed a low negative correlation between soil depth and slope (r = -0.253, n =

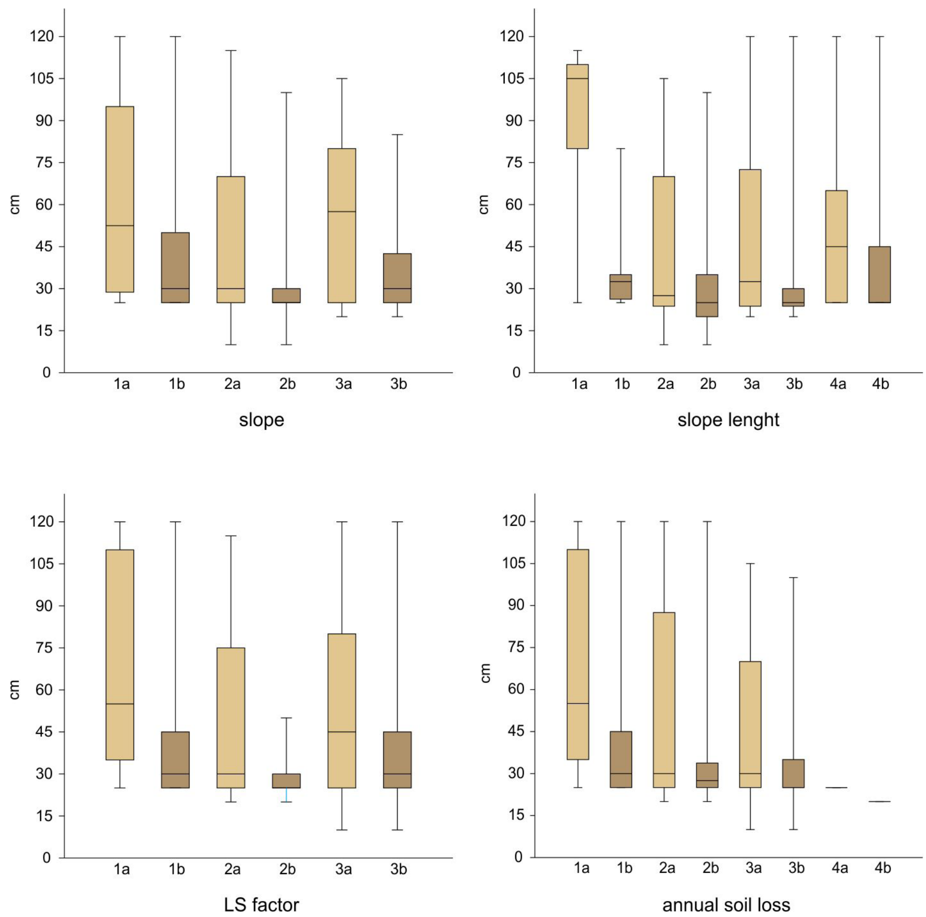

Fig. 8. Slope 1 (0°–3°), 2 (3°–6°), 3 (>6°), slope length 1 (0–200 m), 2 (200–400 m), 3 (400–600 m), 4 (>600 m), LS factor 1 (0–1), 2 (1–5) and 3 (>5), potential soil loss (t/ha/year) 1 (0–4) 2 (4–10), 3 (10–30), 4 (>30), a - total soil depth, b - humus horizon thickness.

71, p = 0.033). Similarly, we identified a low negative correlation between humus thickness and slope (r = -0.199, n = 71, p = 0.097). Upon removing Phaeozem from the database, the correlation between slope and soil depth/humus horizon thickness increased. Specifically, we found a moderate negative correlation between soil depth and slope (r = -0.313, n = 68, p = 0.009), while confirming a moderately strong negative correlation between humus thickness and slope (r = -0.374, n = 68, p = 0.002).

Slope length

In addition to the slope, the slope length also has a significant influence on the course and intensity of erosion. The flow path length was divided into four categories (Fig. 9). Category 0–200 m was represented on 4.28 ha (12.47%), category 200–400 m on 10.30 ha (29.98%), category 400–600 on 12.33 ha (35.90%), and category >600 m was represented on 7.43 ha (21.65%).

In the observed area, both soil depth and humus horizon thickness show a slight increase with the lengthening of the slope. This observation confirms the occurrence of erosion-accumulation processes. However, this pattern does not hold for slopes with a length of 0–200 m, situated on the plateau in the shoulder area, where both total soil depth and humus horizon thickness were found to be the highest (Table 4, Fig. 8). Gabriels (1999), Kinnell (2000), and Jiang et al. (2021) reported that on shorter slopes, water primarily transports particles released by water droplets with minimal surface runoff. However, on longer slopes, the erosive effect of accumulated water becomes more pronounced (Liu et al. 2000). This suggests that more pronounced erosion processes can be expected on longer slopes, a finding that has been confirmed. In the categories of flow path length, we analyzed the total soil depth and the humus horizon thickness. In the category 0–200 m (mean 121.46 m, n = 8), the soil depth ranged from 25 to 115 cm (mean 91.25 cm). This category mainly comprised Cutanic Luvisols and Cutanic Luvisols with accumulated form. The humus horizon varied from 25 to 80 cm (mean 36.88 cm). For the category 200–400 m (mean 307.82 m, n = 22), the soil depth ranged from 10 to 105 cm (mean 42.73 cm), with predominance of Regosols and a lesser presence of Cutanic Luvisols. Phaeozem was identified in a single soil probe, while the humus horizon thickness varied from 10 to 100 cm (mean 36.23 cm). Moving to the category 400–600 m (mean 495.64 m, n = 26), the soil depth ranged from 20 to 120 cm (mean 32.31 cm). Here, Regosols, Cutanic Luvisols, and eroded forms of Cutanic Luvisols were primarily represented. The presence of Regosols and eroded forms of Cutanic Luvisols

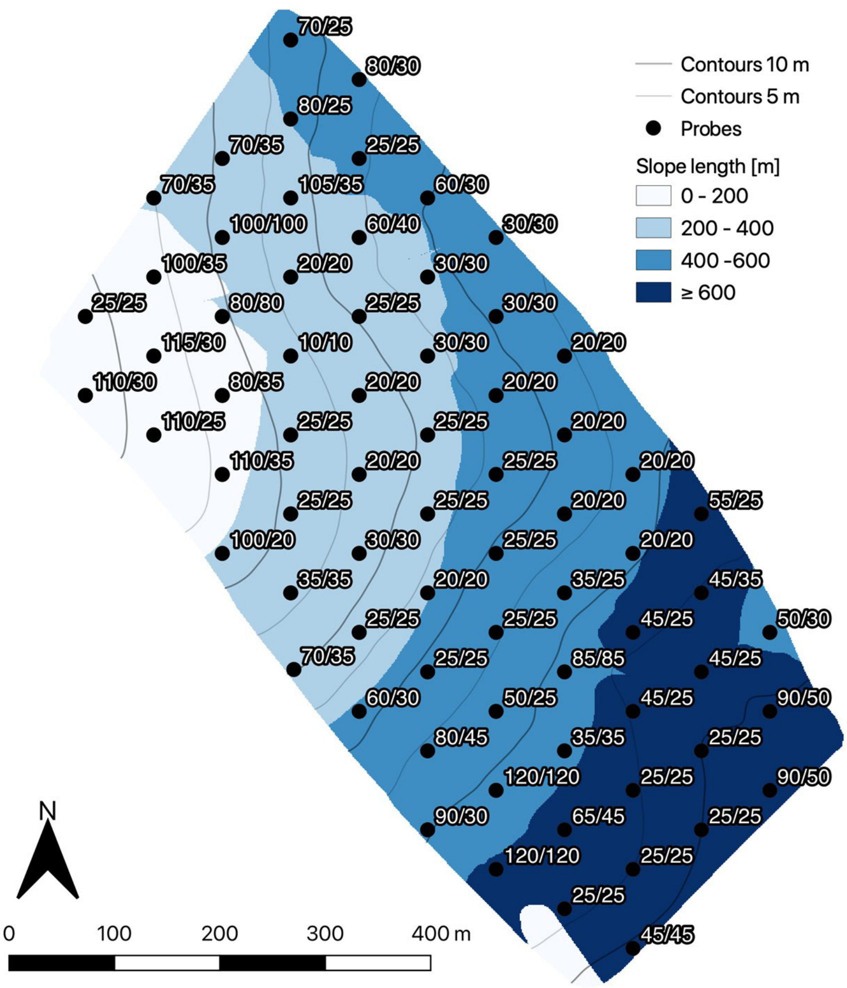

Fig. 9. Slope length of the area and the total soil depth/the humus horizon thickness.

in this category suggests ongoing erosion processes. The positive relationship between erosion rates and slope length on arable land was observed by research (Cerdan et al., 2010; Govers, Poesen, 1988; Whiting et al., 2001). Also, Govers (1991) reported that erosion on arable land rates increase with slope length. Also were Phaeozem and Colluviosol identified. The thickness of the humus horizon varied from 20 to 120 cm (mean 32.31 cm). In the category >600 m (mean 690.45 m, n = 15), the soil depth was in the range of 25–120 cm (mean 51.33 cm). In this category, deeper soils Cutanic Luvisol, Cutanic Luvisol with accumulated form were mainly represented, and less Regosol. Colluviosol was also present. The thickness of the humus horizon varied from 25 to 120 cm (mean 38.00 cm).

We found a low negative correlation between soil depth and flow path length (r = -0.221, n = 71, p = 0.06). No correlation (r = 0.08, n = 71, p = 0.498) was confirmed between humus thickness and flow path length even though we have identified erosion-accumulation processes. Extensive research has been carried out on the relationship between slope length and erosion and accumulation of soil material, resulting in changes in total soil depth and humus horizon thickness. This is reported by Han et al. (2019) and Kinnell, (2009) who also point to the importance of rainfall intensity. Norton et al. (2007) and Han et al. (2019) state that the relationship is obvious, but there are differences between locations with different slope lengths.

LS factor

The effect of slope gradient and slope length (LS factor) on erosion intensity is expressed as a combination of slope gradient factor "S" and slope length "L." This factor is also referred to as the topographic factor, and it plays a crucial role in identifying representative surface runoff paths, defining the area's runoff conditions. Higher LS factor values tend to be in areas where runoff becomes concentrated. We assessed the combined LS factor across three categories (Fig. 10). Category 0–1 covered 3.49 ha (10.18%), category 1–5 encompassed 18.96 ha (55.19%), and category >5 was represented on 11.89 ha (34.63%).

In the LS factor categories, we analyzed both the total soil depth and the thickness of the humus horizon. In category 0–1 (mean 0.55, n = 7), the soil depth ranged from 25 to 120 cm (mean 65.71 cm) (Table 4, Fig. 8). The humus horizon thickness varied from 25 to 120 cm (mean 44.29 cm). This category included representation from Cutanic Luvisols, Cutanic Luvisols with eroded form, Regosols, and Colluviosols. The varied representation of different soil types is associated with the lower values of the LS factor

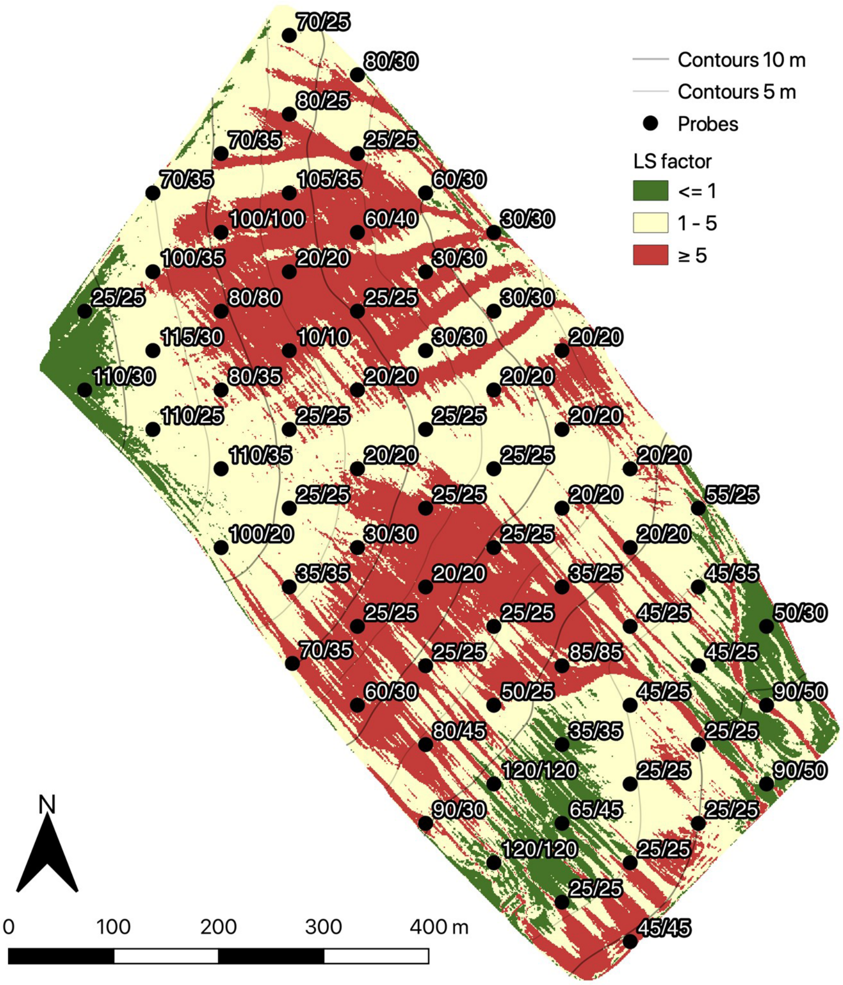

Fig. 10. LS factor of the area and the total soil depth/the humus horizon thickness.

identified in the shoulder, as well as in the lower position of the slope. Moving to category 1–5 (mean 3.25, n = 41), the soil depth ranged from 20 to 115 cm (mean 48.17 cm). The humus horizon thickness ranged from 20 to 50 cm (mean 27.80 cm). This category included representation from Cutanic Luvisols, Cutanic Luvisols with eroded and accumulated forms, and Regosols.

In category >5 (mean 6.88, n = 23), the soil depth ranged from 10 to 120 cm (mean 52.39 cm). The thickness of the humus horizon varied from 10 to 120 cm (mean 40.00 cm). Mainly, Regosols and Cutanic Luvisols with eroded forms were represented. The presence of these soil types signifies erosion processes occurring on slopes with steeper angles and longer lengths. The higher average values of total soil depth and humus horizon thickness are attributed to the prevalence of deep Phaeozems, which are also found on steeper slopes. No linear relationship (r = -0.068, n = 71, p = 0.576) was confirmed between total soil depth and the LS factor. Similarly, no relationship (r = 0.067, n = 71, p = 0.578) was confirmed between humus horizon thickness and the LS factor. However, this lack of correlation does not negate the occurrence of erosion-accumulation processes at the site, as we have observed both eroded and accumulated forms of soil types. We attribute the lack of confirmation of the relationship between LS and soil depth to the diversity of soil types, encompassing both zonal and azonal soils with different pedogenesis. In another investigated area within the Hronská pahorkatina hill land, the LS factor was confirmed to be the most significant in the development of erosion processes (Petlušová et al., 2021b)relief shapes, aspect, slope length, combination slope length (L. The significance of the LS factor in relation to erosion processes was confirmed by Mohammed et al. (2020) in the northern part of Syria on slopes with disturbed vegetation cover. Also, Cossart et al. (2020), who followed him in the vineyards of Burgundy, France.

Potential annual soil loss

In the categories of annual soil loss (Fig. 11), we analyzed the total soil depth and the humus horizon thickness. In the category of0–4 t/ha/year (mean 1.78, n = 11), the soil depth was in the range of 20–120 cm (mean 66.46 cm) (Table 4, Fig. 8). Cutanic Luvisols, and accumulated were mainly represented, less Regosols, and Colluviosols. The thickness of the humus horizon varied from 25 to 120 cm (mean 40.45 cm). In the 2nd category of 4–10 t/ha/year (mean 6.59, n = 24), the soil depth ranged from 20 to 120 cm (mean 53.96 cm). This category was characterized by the representation of Regosols, Cutanic Luvisols, and accumulated Cutanic Luvisols. The humus horizon thickness varied

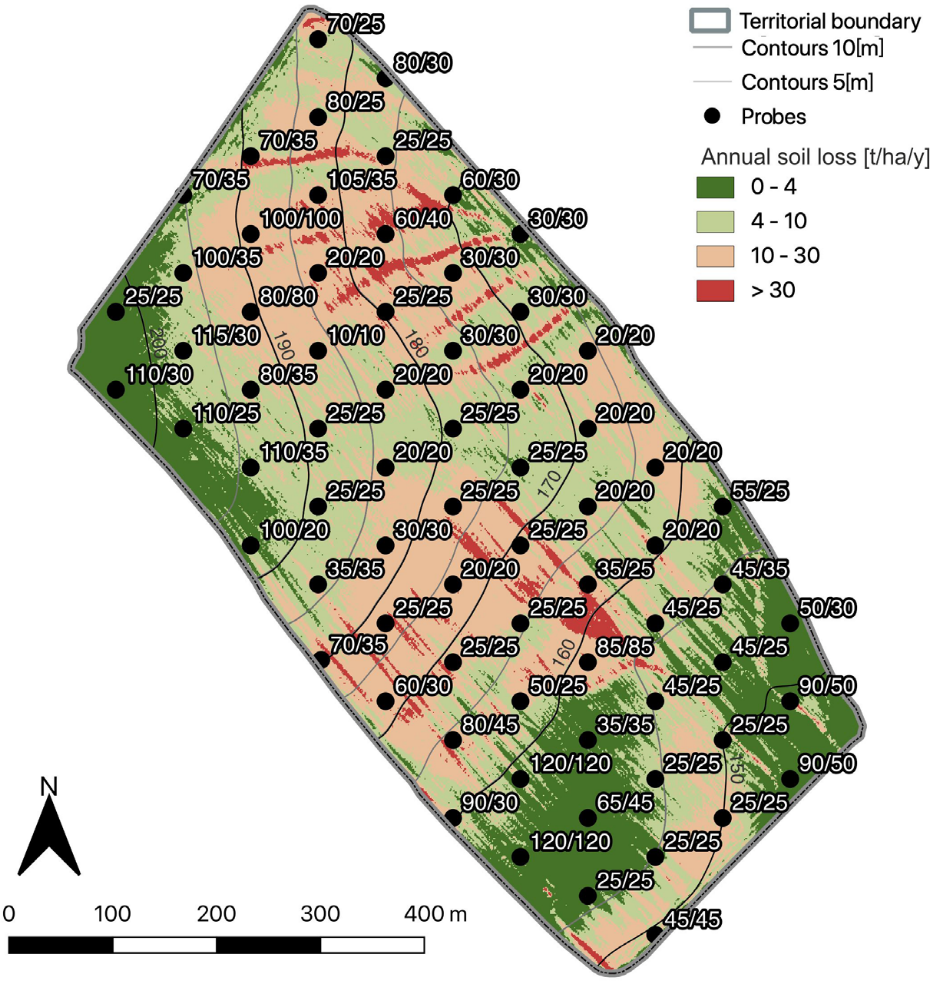

Fig. 11. Annual soil loss of the area and the total soil depth/the humus horizon thickness.

between 20 and 120 cm (mean 32.08 cm). For the 3rd category of 10–30 t/ha/year (mean 15.31, n = 35), the soil depth ranged from 10 to 105 cm (mean 44.43 cm). The humus horizon thickness varied from 10 to 100 cm (mean 31.86 cm). This category was characterized by the representation of Regosols and eroded Cutanic Luvisols. There were three sondes with Phaneozem in small depressions. For the category exceeding 30, we had only one value (44.39, n = 1), the soil depth was 25 cm, and the humus horizon thickness was 20 cm. Regosols was found here. Across all soil depth categories, we did not observe a correlation between soil depth and annual soil loss (r = 0.370, n = 71, p = -0.107) (Hartemink et al., 2020). Similar to Zhidkin et al. (2016), we identified a strong correlation between humus horizon thickness and annual soil loss (r = 0.820, n = 71, p = -0.027).

Conclusion

The study has provided valuable insights into the spatial distribution of soil types, their depth, and their susceptibility to erosion and accumulation processes in the study area. The humus horizon thickness depends on the total depth of the soil. Deep soils with accumulated form have a thick humus horizon that is often the same as the soil total depth. Eroded soils and Regosols often have a ploughed A/C horizon. The presence of these forms indicates the presence of erosion-accumulation processes. Based on the evaluation of selected relief parameters in relation to the total depth of the soil and the thickness of the humus horizon, we found:

1. Slope: We confirmed the relationship between slope, total soil depth, and the humus horizon thickness. On slopes with a higher slope, occurred mainly shallow and eroded soils.
2. Slope length: The relationship between the slope length has not been clearly confirmed in our study area. We found an increase in the total soil depth and the humus horizon thickness with the increasing slope length. We recorded the deepest soils in the upper part with a small slope length. This is a plateau with the occurrence of a recent soil profile less affected by water erosion.
3. LS factor: We did not confirm the relationship between the LS factor, total soil depth, and humus horizon thickness in the study area.
4. Soil loss: In soil depth categories, we did not observe correlation between soil depth and annual soil loss, but we identified a strong correlation between humus horizon thickness and annual soil loss.

The results can be valuable for land management and conservation efforts aimed at achieving the objectives of the Common Agricultural Policy, either through the implementation of biostripes or by employing antierosion measures, especially in areas where agricultural practices are common and erosion control is crucial. Further research and monitoring of eroded soils are recommended to gain a better understanding of the impact of these processes on soil properties and composition. It is essential to build on the principles of sustainable land management to improve the ecosystem services of the agricultural landscape. Ensure good soil structure, e.g. through intercropping and proper crop rotation. Avoid accelerated runoff e.g. by contour farming. In locations with the highest values of potential soil loss and high slope gradients, grow crops with an antierosion effect or apply biostripes or linear woody vegetation.

In current agricultural production, there is a huge impact of climate changes and their consequences on soil health. Morphological factors combined with soil management methods at the study site have the most significant influence on water erosion development, but they also serve as a tool for its prevention. The goal is to protect against pedodegradation processes by transitioning to sustainable land use.

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VEGA 1/0342/22 Identification, evaluation, and consolidation by erosion-threatened hill lands in the lowland regions of Slovakia.

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