Spatial distribution of soil depth in relation to slope as a consequence of erosion-accumulation processes in loess lowland hills of Slovakia

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Abstract

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In our study, we examined the influence of slope gradient on erosion processes and present soil formation and change on loess hills. We analysed data from the two study areas and found that slope gradient is a significant factor influencing soil depth as well as humus horizon thickness. At the Báb locality, we observed a negative correlation between slope gradient and soil depth ($r = -0.206$, $p < 0.05$) and a negative correlation between slope gradient and humus horizon thickness ($r = -0.227$, $p < 0.01$). At the Nová Vieska locality, there was a negative correlation between slope gradient and soil depth ($r = -0.334$, $p < 0.02$), as well as between slope gradient and humus horizon thickness ($r = -0.356$, $p < 0.01$). These findings confirm that slope gradient is a key factor influencing soil formation in loess hills, and has a significant impact on its depth and soil profile. The analysis revealed that a critical slope of 3° significantly influences soil formation, with shallower soils and a thinner humus horizon occurring on steeper slopes. Our findings have important implications for planning erosion control measures and soil management depending on the location and slope gradient. Overall, our work provides insights into soil formation processes in loess hills and contributes to a better understanding of the interactions between slope gradient and erosive processes.

Keywords

erosive processes, humus horizon thickness, loess lowland hills, slope, soil depth

Introduction

In the context of the *Thematic Strategy for Soil Protection* (2006), several soil threats affecting its properties and fertility have been identified. Among them are erosive processes, considered the most severe soil degradation processes. They lead to the complete loss of topsoil and thus to soil degradation. Erosive processes occurring in agriculturally utilized landscapes have been the focus of research attention for several decades due to their negative impacts (Guo et al., 2022; Kirkby et al., 2000; Liu et al., 2020; Panagos et al., 2015; Tao et al., 2022). On the territory of Slovakia, the dominant group of erosive processes is erosion caused by rain and surface runoff of precipitation – water erosion. The data from most authors agree that more than half of the agricultural land area in Slovakia is affected by erosion. Juráň et al. (1990) reports that 55% of the agricultural land area is affected, Bielek (2008) reports 56%. Erosive processes on agricultural land negatively affect the quantitative and qualitative properties of the soil. They cause degradation of the fertile soil layer and reduction in the depth of the soil profile (Klimowicz and Uziak, 2001). Igaz et al. (2018) state that repeated erosion reduces the thickness of the soil profile and sometimes leads to the exposure of the bedrock soil layer, also reducing its fertility, especially through the loss of fine particles. This manifests itself as changes in soil

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structure, a decrease in organic and mineral material, ultimately leading to a reduction in soil fertility (Tobiašová et al., 2023). In the conditions of the Danube hill lands, belonging to most fertile regions of Slovakia, a significant relationship between the humus horizon and the formation and spread of Regosols is observed (Fulajtár and Janský, 2001). Factors contribute to the processes of modelling potential soil loss, designing erosion control measures, optimizing land use, and so forth (Petlušová et al., 2021).

Significant indicators of erosive processes are changes in the soil profile, which are manifested by alterations in the thickness of soil horizons (such as the humus horizon) and subsequently in soil depth, which is a determining factor of soil productivity. The severity of changes in the soil profile, soil horizons, and soil depth can vary and depends primarily on the intensity of erosion. It also depends on the properties of the affected soil and its parent rock. Changes are most noticeable in soils with a significantly differentiated soil profile, especially shallow soils on rocky parent materials. Also, soils with well-developed A and B horizons, characterized by higher fertility compared to the C horizon, exhibit prominent changes. Such cases are primarily represented by chernozems and brown soils in loess areas in the conditions of Slovakia (Fulajtár and Janský, 2001). For each soil type, there is a characteristic sequence of genetic soil horizons, parent material, and possibly underlying rock. On slopes with inadequate vegetation cover, accelerated erosion leads to the transport of fine soil material (most commonly particles smaller than 0.01 mm) from the upper part of the slope downslope, where it subsequently accumulates. These deposits can increase the thickness of the topsoil horizon several times compared to its original thickness. Kenderessy (2016) states that in the case of Luvisol (Aric), the typical sequence of diagnostic horizons is as follows: on the surface, there is an aric ploughed horizon, below it a subsurface luvic (Bt) horizon, which gradually transitions into a transitional horizon (B/C), which is lighter, and below it, there is an even lighter (C) horizon formed by the parent material. As a result of erosive processes, this profile in the lower part of the slope along the footslope transforms in such a way that the A horizon, compared to its position at the top of the slope, becomes lighter. Below it, a transitional A/C horizon is formed. Beneath the A/C horizon, only the C horizon is formed by the loess parent material. This transformed soil can be characterized as Regosol (Aric), which is visually manifested as exposed light patches mainly on convex slopes. At the foot of slopes, on the contrary, accumulation processes occur, where the original cultic ploughed A horizon is overlaid by accumulated deposits, leading to the formation of Colluviosols. These processes most commonly affect loess hills in Slovakia, where in some areas with the highest predisposition (convex slopes, inadequate erosion protection), Regosols and eroded forms of soil types are spreading extensively. When evaluating changes in the soil profile, it was assumed that erosional and depositional processes result in changes in soil depth, alterations in horizon thickness, and modifications of the sequence of soil horizons in the soil profile.

The aim was to determine whether the slope significantly influences soil depth and the humus horizon thickness. We assume that, due to erosional and depositional processes in the conditions of loess hill land with predominantly intensive agricultural land use, steeper slopes will have shallow soils with less developed soil profiles as a result of soil erosion. Additionally, we anticipate that in the footslope parts of the slope, there will be deeper soils due to soil accumulation with colluvial material.

Materials and methods

Study area

Changes in the soil profile were analysed in two cadastral territories characterized by predominantly intensive agricultural land use. These areas are located in hill land relief type in the cadastral territories of Báb (Nitrianska pahorkatina hill land) and Nová Vieska (Hronská pahorkatina hill land) (Fig. 1). The combination of dissected relief, intensive agriculture, and parent material susceptible to soil erosion categorizes the studied areas as among the most erosion-prone in Slovakia.

Báb is characterized by a mosaic of large-scale fields with conventional tillage, vineyards, and forests on the slopes. The total area of the territory is 2,009 ha. The relief consists of smoothly modelled slopes with shallow periglacial depressions (Mazúr et al., 1980). A typical feature of the area are the plateaus with a slope of up to 3°. The elevation ranges from 160 to 210 m asl. The slope varies between 0 and 20°. The geological structure consists of Neogene sediments forming the substrate (coarse gravelly and sandy complexes, and sandy clays). In the overlying layer, Quaternary sediments (clays, sands, and silty to sandy loess, and loess loams) are developed throughout the area (Pristaš, et al., 2000).

Nová Vieska is in the alluvium of the Paríž stream. It is bordered by the Strekov terraces with a mosaic of large-scale fields with conventional tillage and vineyards. The total area of the territory is 1,760.50 ha. The area features an erosional-denudational relief of low land hills and undulating plains with river terraces and loess tables (Mazúr et al., 1980). The slope of the relief ranges from 0 to 17°. The elevation varies between 120 to 226 m asl. The geological structure of the area, according to (Biely et al., 2002), is formed by Neogene sediments – grey and variegated clays, sands, and gravels. The Quaternary cover consists of fluvial and aeolian sediments – sands, sandy gravels, and sands on terraces with a covering of loess and loess loams (Maglay and Pristaš, 2002). In both areas, the average annual temperature ranges from 8.5–10 °C, the average annual rainfall is 550–600 mm and north-westerly winds prevail.

Mapping the spatial distribution of soil types

The aim of the mapping was to identify the spatial distribution of soils, and forms based on soil erosion-accumulation characteristics through field research by used Slo-

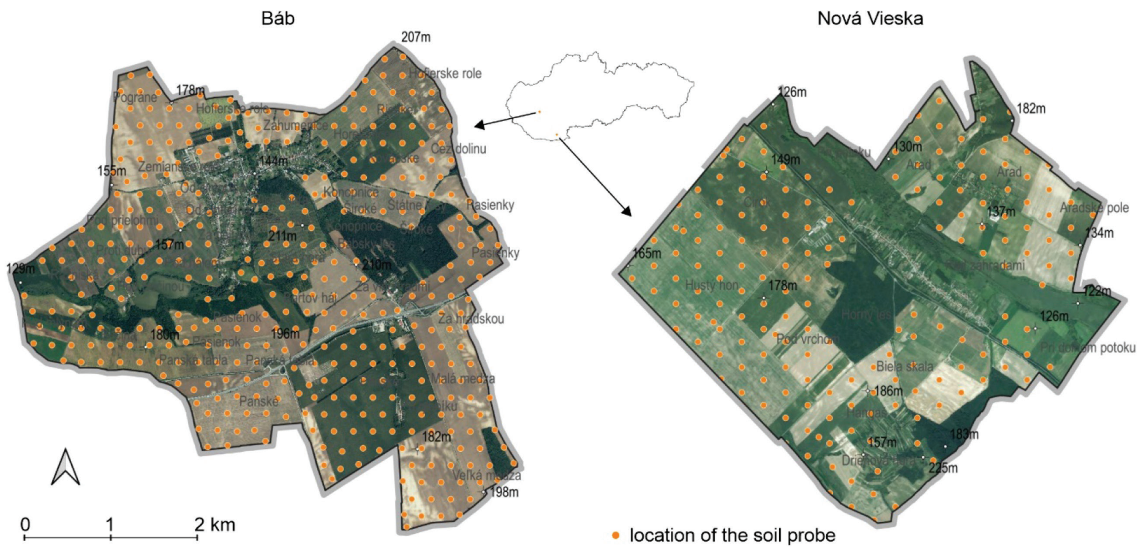

Fig. 1. Delimitation of the study area within the Slovak Republic, aerial view of the configuration of agricultural land mosaic, and location of soil probes. Source: Geodesy, Cartography, and Cadastre Authority of the Slovak Republic, National Forest Centre (2020).

Table 1. Soil depth categories and soil classification according to Slovak Soil Classification (Societas Pedologica Slovaca, 2014)) in Báb and Nová Vieska

Soil depth	Soil classification	Codes of soil
Shallow soils	Regosol (Ochric)	RGoh
(<30 cm)	Regosol (Aric) with a humus horizon thickness of up to 30 cm	RGai
Medium-deep soils	Regosol (Aric) with a humus horizon thickness of more than 30 cm	RGai
(30–60 cm)	Haplic Chernozem with a humus horizon thickness of more than 30 cm	CHha
	Haplic Chernozem, form eroded	CHhaee
	Luvic Chernozem with a humus horizon thickness of more than 30 cm	CHlv
	Luvic Chernozem, form eroded	CHlvee
	Haplic Luvisol with A horizon thickness of up to 20 cm	LVha
	Haplic Luvisol, form eroded	LVhaee
Deep soils	Haplic Chernozem with a humus horizon thickness of more than 60 cm	CHha
(>60 cm)	Haplic Chernozem, form accumulated (colluvial soil)	CHhaea
	Luvic Chernozem with a humus horizon thickness of more than 60 cm	CHlv
	Haplic Luvisol with A horizon thickness of more than 20 cm	LVha
	Haplic Luvisol, form accumulated (colluvial soil)	LVhaea

Source: field research Petlušová, Petluš, Mederly, Hreško, Moravčík (March 2020–April 2021).

vak Soil Classification (Societas Pedologica Slovaca, 2014). The field research was conducted in the Báb area from March to April 2021, with a total of 411 soil probes. In Nová Vieska, the field research was conducted in March 2020 and March 2021, totalling 198 soil probes. A hexagonal grid was used for the spatial distribution of soundings, with the soundings in the cadastral area of Báb spaced 230 m apart, and in Nová Vieska spaced 250 m apart. However, the placement of some soundings was refined based on terrain conditions and land use. The distance between points was chosen to represent a broader area of the mapped territory. The soil probes were located on agriculturally utilized land, including arable land, vineyards, orchards, gardens on the outskirts of villages, and permanent grassland. To verify, an Edelman soil auger with the capability of drilling up to 120 cm depth and a diameter of 50 mm was utilized. The investigation included determining soil depth, humus horizon thickness, presence of soil horizons, plow depth, character of the soil-forming substrate, and thickness of accumulated material.

Soil depth analysis

Soil depth is crucial for efficient soil management and sustainable agricultural practices. It is the depth of the entire soil profile from the soil surface to the parent matter. The analysis of soil depth included soil types such as Chernozems, Regosols and Luvisols, which developed on unconsolidated non-alluvial sediments on slopes of lowland hills. Soil types such as Cultizem, Anthrosol, Fluvisol, Gleysol, Organosol, and peat soil were not evaluated because they have a different pedogenetic development (origin influenced by anthropogenic activities, developed on alluvial sediments of lowland rivers, initial soils, etc.). Excluding these soil types, 395 soundings were analysed in the Báb area and 177 soundings in Nová Vieska. Based on the data from field research, soil classification according to category of soil depth was processed. The categorization followed the classification of soil depth by (Džatko and Sobocká, 2009) used under the conditions of Slovakia, which classifies soils based on depth as shallow (up to 30 cm), moderately deep (30–60 cm), and deep (60 cm and more). The classification of identified soil types based on soil depth is provided in Table 1.

During the analysis of changes in soil depth, the assumption was made that erosional and accumulative processes lead to alterations in the soil horizon thickness or changes in the sequence of soil horizons (Kenderessy, 2016; Labaz et al., 2022). In the sloping positions of loess hills without vegetative cover, soil material is subjected to erosion. As a result, there is a reduction in the thickness of the A horizon or its loss at the upper part of the slope and an increase in its thickness at the lower part of the slope (Fig. 2). Under the conditions of the loess hills of Slovakia, a similar phenomenon can be observed in the brown earths, where the A horizon to part of the Bt horizon is lost. The analysis of the changes in the soil horizons thickness was carried out on the basis of the description of the soil profiles, according to (Bielek and Šurina, 2000):

Chernozem – A up to 60 cm, A/C 60–(75) 80 cm, C (75) 80 cm and more

Luvisol – A up to 20 cm, Bt 20–60 (70) cm, Bt/C 60 (70)–80 cm, C 80 cm and more

Regosol – A up to 25 cm, A/C 25–35 cm, C 35 cm and more.

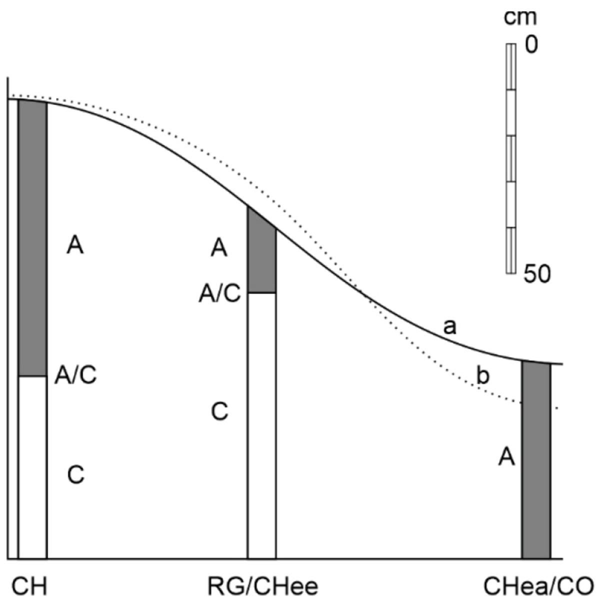

Fig. 2. Typical catena and change in the arrangement of soil horizons on slope in the model areas due to erosion-accumulation processes. a – recent surface, b – original surface, CH – Chernozem, RG/CHee – Regosols and Chernozem eroded, CHea/CO – Chernozem accumulated/Colluviosol.

Based on the thickness of the individual horizons in the soils studied, the soil form was determined to be eroded or accumulated (Societas Pedologica Slovaca, 2014).

Analysis of slope and changes in soil depth and humus horizon thickness

Slope is the most important morphometric parameter of the relief, which is a determinant of the origin and intensity of slope processes. It is significant in terms of land use and agricultural land management (Assouline and Ben-Hur, 2006; Petlušová et al., 2021; Tao et al., 2022). For the analysis, we used the DMR3.5 Digital Elevation Model with a resolution of 10 m (Geodesy, Cartography, and Cadastre Authority of the Slovak Republic, 2023).

We used the slope categories: 0–1°; 1–3°; 3–7°; >7°, which are based on the slope categories by (Ilavská et al., 2005). Correlation analysis was used to determine the relationships between the soil depth and soil humus horizon thickness. Significant Pearson correlation coefficients were tested at $P < 0.01$ and $P < 0.05$.

Results and discussion

Spatial distribution of soils

In both localities, Chermozems, Regosols and fewer Luvisols are predominant. The soil cover is represented by an erosion-driven mosaic of Chernozems, preserved mainly on the plateaus, Regosols on back-slopes exposed to the removal of topsoil and colluvial soils in the concave parts of relief (Zádorová et al., 2023). Chernozems occur mainly on plateaus but also on gentle slopes in various parts of the areas. This was also observed by Labaz et al. (2022) in plain positions in south Poland. They state that in the above positions are still preserved, non-eroded or weakly eroded Chernozems typically having a 60–80 cm humus horizon thickness. The accumulated form of chernozems in both study areas is situated in valley and concave positions. In lowland hills characterized by dissected surfaces, the effect of soil deposition in concave slope positions in the Czech Republic is also observed by Zádorová et al., 2023. In Central European conditions by Juřicová et al., 2022; Kühn et al., 2017; Rodzik et al., 2014. Euric Regosol (Aric, Protocaltic, Ochric) Regosols occur on the middle and higher slopes usually as a result of erosion processes on loess and loess loams. Cultivated Regosols - Euric Regosol (Aric, Protocaltic) predominate in eroded agricultural areas of the lowland hills. Sporadically, Regosols have been observed on sand-silty Neogene weathering rocks. The formation of weakly developed Regosols as a result of truncation of former Luvisols has already been confirmed by Klimowicz and Uziak (2001) in undulating areas of the Lublin Upland in Poland. Anthrosol, Hortic Antrosol, Fluvisol, Gleysol, Histosol, Fluvic Gleyic Chernozem, which did not enter into further analyses, were identified in the cadastral area of Báb in 16 probes and in Nová Vieska in 20 probes. On the slopes, the eroded soils were visually particularly striking due to the colour contrast of the A horizon, or in the case of the Luvisols the B horizon, against the light-coloured loess C horizon. In the Nitrianska pahorkatina lowland hills this was also observed by Fulajtár and Janský (2001). In contrast, accumulated soils in concave parts have a darker A horizon. The colour of the soil varied depending on the colour of the soil material from the slope. Where lighter shades of soil colour occurred in the concave part of the slope, these were loess materials with low humus content from the upper parts of the slope. Zádorová et al. (2008) observed a similar phenomenon in chernozemic loess areas when delineating colluvial soils.

Soil depth as an indicator of erosion-accumulation processes

The main indicators of erosion-accumulation processes are changes in soil depth and in the humus horizon thickness (Batista et al., 2023; Świtoniak, 2014). The changes were mainly evident in the probes where Chernozems and Luvisols types were identified with the forms eroded, accumulated and in Regosols too. Changes in soil depth and humus horizon thickness on Chernozems and Regosols, in this context, are also reported by Labaz et al. (2022), Świtoniak (2014). The representation of soil types in soil depth categories is shown in Table 2.

At both localities, shallow eroded soils are found mainly in the convex slope positions, while deep and accumulated soils in the concave positions of slopes. On the convex parts of the slopes there is a loss of the surface soil horizon (soil truncated) and on the concave surfaces there is deposition of colluvial material (accretion) (Lang, 2003; Świtoniak, 2014). Świtoniak (2014) found that the most intensive erosion zone occurs on the upper, convex parts of slopes with an inclination above 2°, and within the tops of hills. The analysis shows that in Báb, a group of soils with eroded forms (Chernozem, Luvisol and Regosol) (Table 2) was significantly represented among the erosion-accumulation forms. Soil depth ranged from 20–100 cm with a predominance of medium deep soils. Of the accumulated forms, Chernozem and Luvisol are represented in the area, with a depth of 65–100 cm. In Nová Vieska, a group of soils with eroded forms was significantly represented by the erosion-accumulation forms Chernozem, Luvisol and Regosol. Soil depth was from 20 to 100 cm and deep soils predominated, and of the accumulated forms, Chernozem and Luvisol are represented (Fig. 3, Table 3). From the analyses, it becomes apparent that on soils exhibiting erosive forms, both soil depth and thickness of the humus horizon are lower compared to soils with accumulated forms. This is confirmed by Zhidkin et al. (2023), who observed changes in humus horizon thickness in the Eastern European Plain, where the soil material is carbonate loess. Papiernik et al. (2007) reported that in west central Minnesota, soils in areas of high soil loss were characterized by truncated soil profiles and low humus horizon thickness. In accumulation areas deep soils with large humus horizons dominated. The humus horizon thickness in both areas correlated with soil depth in all soil depth categories. In Báb, a significant relationship between total soil depth and humus horizon strength ($r = 0.808$, $n = 395$, $p < 0.01$) was confirmed. A similarly strong relationship was observed at Nová Vieska ($r = 0.828$, $n = 177$, $p < 0.01$). In Nová Vieska, the soils are deeper with a larger humus horizon thickness (Fig. 4). This is related to the relatively lower relief dissection Labaz et al. (2018), which enters as one of the factors of soil development for the formation of deeper soils, together with the relief shapes (Smetanová et al., 2017; Świtoniak, 2014) and geological structure

Table 2. Representation of soil types in soil depth categories

Soil		Báb Number of probes	Báb Number of probes in category	Báb Soil depth (cm)	Báb $\bar{x}$ soil depth (cm)	Nová Vieska Number of probes	Nová Vieska Number of probes in category	Nová Vieska Soil depth (cm)	Nová Vieska $\bar{x}$ soil depth (cm)
1	RGoh	8	67	20–30	27.73	–	34	20–30	28.38
	RGai	59				34			
2	RGai	37	208	32–60	47.00	6	65	35–60	49.69
	CHha	138				9			
	CHhaee	25				46			
	CHlv	4				2			
	CHlvee	3				–			
	LVha	1				1			
3	CHha	37	120	65–100	83.54	47	78	65–100	85.00
	CHhaea	30				20			
	CHlv	42				10			
	LVha	–				1			
	LVhaea	8				1			
	CHha	3				–			
		395	395			177	177		

1– shallow (<30 cm), 2 – medium deep (31–60 cm), 3 – deep (>61 cm), *eroded form. Source: field research Petluš, Petlušová, Mederly, Hreško, Moravčík, March 2020–April 2021.

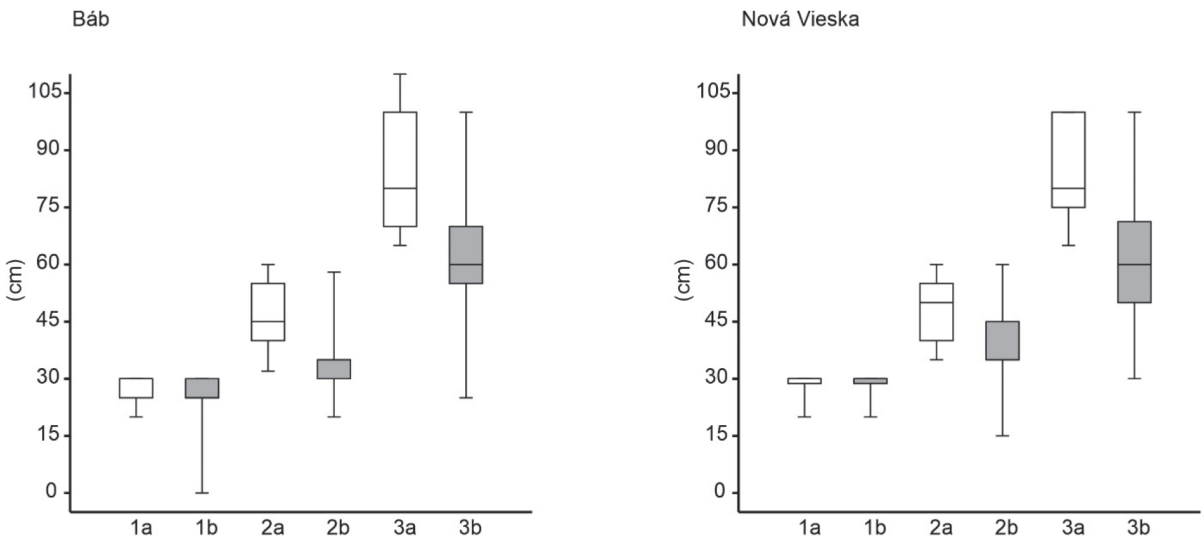

Fig. 3. Soil depth and humus horizon thickness by soil depth category. 1 – shallow soils (<30 cm), 2 – medium-deep soils (31-60 cm), 3 – deep soils (>61 cm), a – soil depth, b – humus horizon thickness.

Table 3. Summary statistic of soil depth (cm) and humus horizon thickness (cm) by the soil depth categories

	Shallow soils		Medium-deep soils		Deep soils		All soils	
	Soil depth	Humus horizon	Soil depth	Humus horizon	Soil depth	Humus horizon	Soil depth	Humus horizon
Báb								
Min.	20.00	0.00	32.00	20.00	65.00	25.00	20.00	0.00
1st Qu.	25.00	25.00	40.00	30.00	70.00	55.00	35.00	30.00
Median	30.00	25.00	45.00	35.00	80.00	60.00	50.00	35.00
Mean	27.73	24.67	47.04	34.46	83.54	61.46	54.86	41.00
3rd Qu.	30.00	30.00	55.00	35.00	100.00	70.00	70.00	55.00
Max.	30.00	30.00	60.00	58.00	100.00	100.00	100.00	100.00
Nová Vieska								
Min.	20.00	20.00	35.00	15.00	65.00	300.00	20.00	15.00
1st Qu.	28.75	28.75	40.00	35.00	75.00	50.00	40.00	30.00
Median	30.00	30.00	50.00	35.00	80.00	60.00	60.00	40.00
Mean	28.38	28.38	49.69	38.00	85.00	62.82	61.16	47.09
3rd Qu.	30.00	30.00	55.00	45.00	100.00	71.25	80.00	60.00
Max.	30.00	30.00	60.00	60.00	100.00	100.00	100.00	100.00

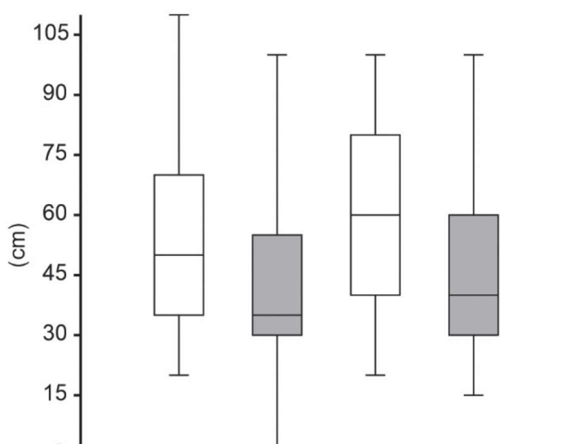

Fig. 4. The soil depth and humus horizon thickness. BA – Báb, NV – Nová Vieska, a – soil depth, b – humus horizon thickness.

(Kabała et al., 2019). The average soil depth in Báb is 54.85 cm, and in Nová Vieska it is 61.15 cm. The case for the humus horizon thickness is similar. In Báb the humus horizon is 41.00 cm and in Nová Vieska 47.10 cm. The humus horizons thickness varied significantly depending on the soil profile position. The thinnest humus horizons were identified in the shoulder and backslope positions. The humus horizons thickness in several cases corresponded to the depth of ploughing. This was confirmed by a distinct or abrupt boundary between the humus horizon and the parent material. Labaz et al. (2022) confirmed this in the shoulder parts of slopes in loess areas in the Proszowice Plateau.

The soil found in the bottom slope parts, less so in the backslope parts, had significantly larger humus horizons. Labaz et al. (2022), Zádorová et al. (2023) observed this in Central European conditions. In Nová Vieska, the humus horizon thickness is higher in all soil depth categories. In Nová Vieska, in the category of shallow soils, soil depth and humus horizon thickness are the same. Only ploughed

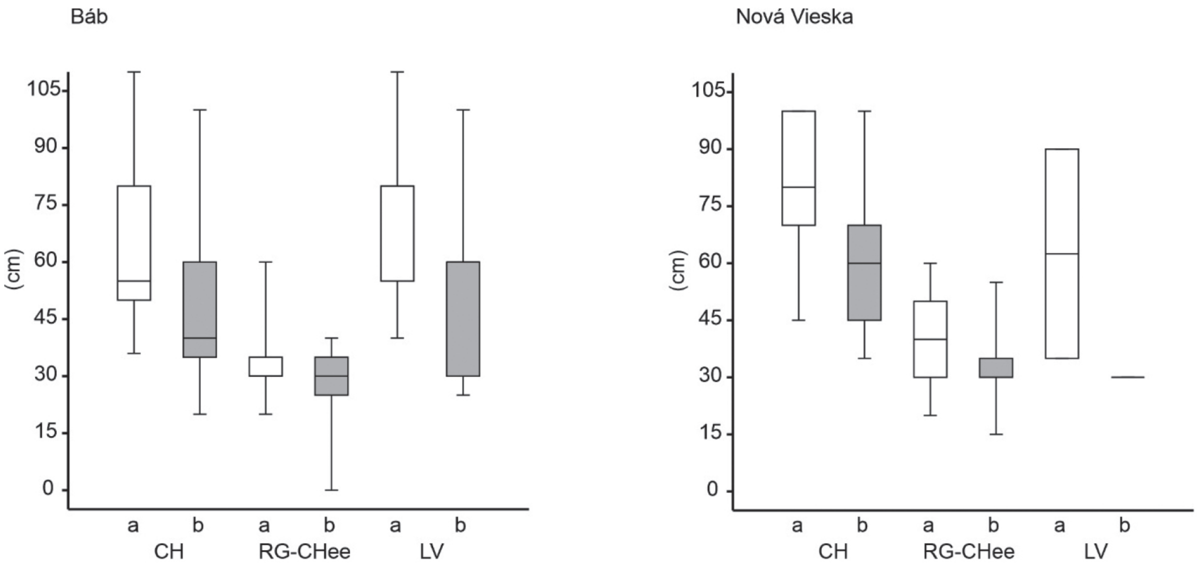

Fig. 5. Soil depth and humus horizon thickness by soil types. CH – Chernozem, RG-Cher – Regosols and eroded Chernozem, LV – Luvisol, a – soil depth, b – humus horizon thickness.

Table 4. Slope categories on agricultural land

Slope (°)	Báb (ha)	Báb (%)	Nová Vieska (ha)	Nová Vieska (%)
0–1	283.89	18.01	252.33	19.40
1–3	797.26	50.57	707.73	54.41
3–7	446.69	26.95	303.80	23.36
>7	70.61	4.47	36.91	2.83
	1,598.45	100.00	1,300.77	100.00

Source: digital relief model DMR 3.5 10m: Geodesy, Cartography and Cadastre Authority of the Slovak Republic, 2020.

Regosols were identified in that category with the same minimum and maximum values in the total depth and humus horizon thickness.

We also analysed soil depth and humus horizon thickness by soil type (Fig. 5). We divided individual soils into three basic groups: Chernozems (CH), Regosols and eroded Chernozems (RG-CHer) and Luvisols (LV).

We have found that at Báb, the average depth of Regosols and eroded Chernozems (N = 129) is only 34.94 cm, and the average depth of the humus horizon is 28.12 cm, which corresponds approximately to the depth of

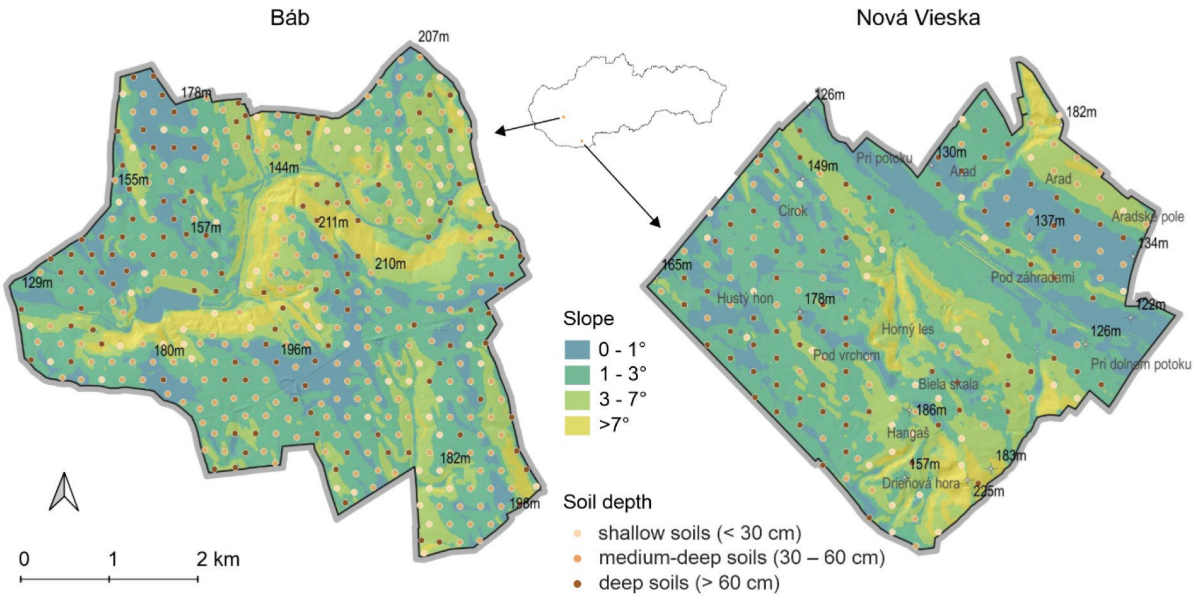

Fig. 6. The spatial distribution of the soil depth and the slope categories. Source: digital relief model DMR 3.5 10m: Geodesy, Cartography and Cadastre Authority of the Slovak Republic, 2020; field research Petluš, Petlušová, Mederly, Hreško, Moravčík, March 2020–April 2021.

ploughing and mechanical mixing of the A and C horizons (Houben, 2008; Świtoniak, 2014). The average soil depth of the other Chernozems (N = 251) is 64.59 cm and the average humus horizon thickness is 47.18 cm. The average soil depth of Luvisol (N=15) is 73.00 cm and the average humus horizon thickness is 49.66 cm. At the Nová Vieska, the depth of the Regosols and eroded Chernozems (N = 87) is 40.57 cm and the humus horizon 33.28 cm. The soil depth of other Chernozems (N = 88) is 81.47 cm and the humus horizon 61.14 cm. The soil depth of Luvisol (N = 2) is 62.5 cm and the humus horizon 30 cm.

Slope

In both localities, the most represented categories range from 1–7°, with a predominance of the category 1–3°, which occupies more than 76% of the area (Table 4, Fig. 6). They are dominated by intensively used arable land. Currently, winter wheat, maize for corn, spring barley, and oilseed rape are the dominant crops.

Most of both localities (with a slope <3°) are suitable for intensive agricultural activity. The moderately undulating topography, together with other factors, has led to the formation of a relatively homogeneous soil cover with a predominance of chernozemic type soils (Labaz et al., 2018). In the higher slope categories (>7°), Regosols are mainly represented. They were formed from the Chernozems as a result of several decades of intensive agricultural use, which may have resulted in the development of erosion processes (Kołodyńska-Gawrysiak et al., 2017; Świtoniak, 2014; Zádorová et al., 2013). In both localities, eroded soils were also identified on plateaus with minimum slope values (<1°), where wind erosion also occurs, especially on soils not covered by vegetation (Sebe et al., 2011). The eroded slope positions are dominated by silty soil texture, indicating degradation of the loess parent material. The soil-forming substrate in both localities is mainly loess and loess loams, which are characterised by high erosion susceptibility. Soils are characterized by high silt content (40–60%), which makes them poorly resistant to erosion processes (Terhorst, 2000). This was observed in Silesian Lowland conditions by Labaz et al. (2018).

Slope and soil depth in the erosion-accumulation processes context

In the processes of erosion and accumulation, the soil horizons thickness and the soil depth change. Changes in soil horizons and eroded soils depth are confirmed by Houben (2008), Liu et al. (2021), Musso et al. (2020). The slope enters the development of erosion-accumulation processes as one of the main factors (Fu et al., 2011; Shen et al., 2016). We assume that with increasing slope, the soil depth and humus horizon thickness decreases. This was also confirmed by (Świtoniak, 2014), who states that the most intense erosion processes occur on the convex parts of slopes with a slope gradient of >2° and at the tops of slopes, where truncation of the humus horizon occurs. In both localities, soil depth decreases with increasing slope and thinning of the humus horizon (Fig. 7). A similar result has already been described by authors Fu et al. (2011), Govers and Poesen (1988). In the loess hill land conditions of Slovakia, a slope of 3° is considered critical (Fulajtár and Janský, 2001; Petlušová et al., 2021). At the Báb locality, 112 (28.4%) of 395 probes were located on slopes >3°, with up to 52 probes (46.4%) in the category of shallow soils up to 30 cm. Regosols were represented, the formation of which is influenced by erosional processes in the conditions of the loess hill lands of Slovakia. Eroded soils were also in the category of medium-deep soils (Regosols, Chernozems). In the range 0–40 cm, 81 probes (72.3%) were identified where the soil depth was reduced and the humus horizon truncated. The effect of slope was also confirmed by Fu et al. (2011) in the Wangjiaqiao watershed, who reported that of a total of 348 sampling sites on parcels with a higher slope, 75% of them had soil thickness in the range 15–75 cm and 69% of them were located on slope >15°. As the increased slope, the proportion of shallow soils gradually increased, which was also confirmed in our study. At the Nová Vieska locality, 52 probes (29.3% of the total 177 probes) were located on slopes >3°. In the shallow soils category up to 30 cm (Regosols), changes in soil depth and humus horizon were identified in 25 probes (46.3%). Medium-deep soils up to 40 cm (Regosols, Luvisols) with erosion processes were identified in 30 probes (55.6 %). In both localities, shallow and medium-deep soils occurred predominantly in the upper and middle parts of the slope, where it was situated on convex landforms. This was observed in the eroded undulating loess plateau in Central Europe by Labaz et al. (2022). They identified eroded shallow soils in the upper parts of the slope and on the ridges ranging from 2 to 10°, and medium-deep soils in the middle parts of the slope and at lower positions ranging from 0 to 6°.

Subsequently, we found the strength of the relationship between slope, soil depth and humus horizon thickness. We found in both localities a statistically significant relationship between the variables analysed. At the Báb locality, there is weak negative correlation between slope and soil depth ($r = -0.257$, $n = 395$, $p < 0.01$). Comparing slope and humus horizon thickness, we similarly found a weak negative correlation ($r = -0.227$, $n = 395$, $p < 0.01$). At the Nová Vieska locality, there is a negative, medium strength correlation between slope gradient and soil depth ($r = -0.388$, $n = 177$, $p < 0.01$) and a negative, medium strength correlation between slope and humus horizon thickness ($r = -0.374$, $n = 177$, $p < 0.01$). In the Trnavská pahorkatina lowland hills, the relationship between slope and changes in soil profile was confirmed by Smetanová et al. (2017). Two groups of data were analysed separately according to slope <3° and >3° (Fig. 8).

We consider the value of 3° to be the critical and decisive value, as confirmed by Petlušová et al. (2021). By analysing the <3° slope dataset, we found no relationship in Báb between slope and soil depth ($r = -0.05$, $n = 263$, $p = 0.378$). Conversely, when slope gradients >3° were analysed, we confirmed a significant relationship between

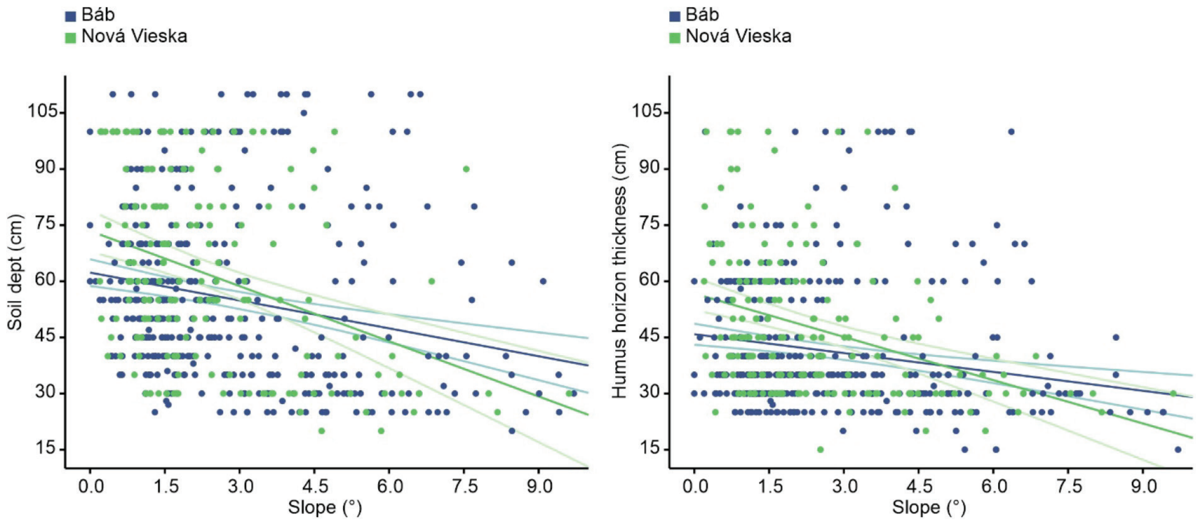

Fig. 7. Linear regression of soil depth and slope. Paler shades show 95% confidence interval.

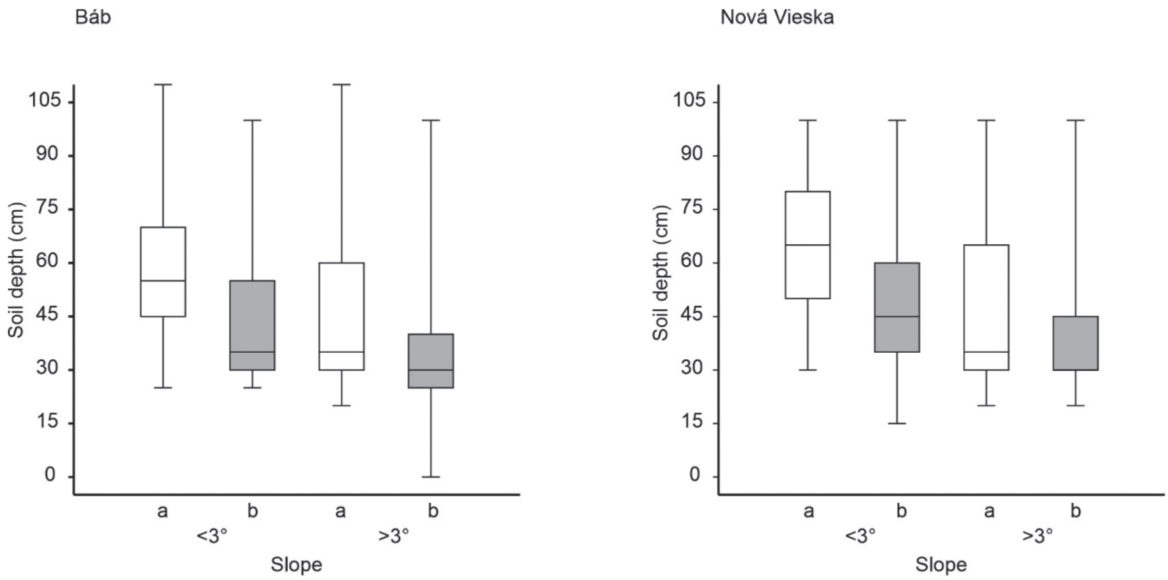

Fig. 8. Soil depth and humus horizon thickness by slope category. a – total soil depth, b – humus horizon thickness.

slope and soil depth ($r = –0.206$, $n = 132$, $p < 0.05$). Similar findings apply when analysing the relationship between slope and humus horizon thickness. We found no relationship between slope and humus horizon thickness ($r = –0.05$, $n = 263$, $p = 0.362$) when analysing slope of <3°. Conversely, when slope >3° were analysed, we confirmed a significant relationship between slope and humus horizon thickness (r = -–0.302, $n = 132$, $p < 0.01$). In Nová Vieska the data behaved similarly. Analysing the slope <3°, we found no relationship between slope and soil depth ($r = –0.09$, $n = 124$, $p = 0.283$). Conversely, when slope gradients >3° were analysed, we confirmed a significant relationship between slope and soil depth ($r = –0.334$, $n = 53$, $p < 0.02$). When analysing slope <3°, we found a relationship between slope and humus horizon thickness ($r = –0.221$, $n = 124$, $p < 0.02$). With slope >3°, we confirmed a significant relationship between slope and humus horizon thickness ($r = –0.356$, $n = 53$, $p < 0.01$). The findings confirm the assumption that with increasing slope, soil depth as well as humus horizon thickness will become truncated under loess hill lands conditions (Labaz et al., 2022; Smetanová et al., 2017; Świtoniak, 2014). When assessing the spatial distribution of soil depth in relation to slope as a consequence of erosion-accumulation processes in loess hill lands, it is important to observe not only the slope but also at which slope position changes in soil depth and humus horizon take place. We confirmed that even in positions with a higher slope, deep soils occur. We identified them in both localities. This is influenced by the shape of the relief, where concave and convex shapes alternate. In concave positions there is braking and accumulation of material, and in convex positions there is accelerated transport resulting in changes in soil depth and humus horizon (Labaz et al., 2022; Świtoniak, 2014; Zádorová et al., 2023).

Conclusion

A study in two localities in loess hill lands intensively used for agricultural activities confirmed that the continuous cover with a predominance of chernozems has gradually transformed into a mosaic of chernozemic and non-chernozemic soils. In addition to Chernozems, Regosols and eroded Chermozems occur on the slopes. Accumulated soils were identified in the footslope and in concave slope positions. An important driving force for spatial soil differentiation in both areas is erosion-accumulation processes supported by intensive use of arable land. In the context of erosion-accumulation processes, we confirmed changes in soil depth and humus horizon thickness. We confirmed a strong relationship between total soil depth and the humus horizon thickness. In relation to the slope, we confirmed that the soil depth as well as the humus horizon thickness decreases with increasing slope. We base our observation on weak and medium correlations. Deep and accumulated soils are also found on higher slopes. These are mainly located in concave positions where, despite the higher slope, there is an accumulation of material. We consider the finding to be significant with respect to the setup of the management of anti-erosion measures. Slope is a decisive and significant factor in the development of erosion-accumulation processes. At positions above 3°, we confirmed the relationship between slope and humus horizon thickness. In these positions, crops with a high anti-erosion effect (clover, grassland, etc.) or crops with a good anti-erosion effect (cereals, legumes, oil rape, intercrops, etc.) should be grown with minimal soil treatment. At positions up to 3°, there is no relationship between slope, soil depth and humus horizon thickness. On these areas it is possible to grow crops with lower anti-erosion efficiency and crops with low anti-erosion efficiency (maize for corn, sunflower, beet, potatoes, etc.). On less erosion-prone sites, anti-erosion agrotechnical measures are applied (contour ploughing, mulching, grassing, etc.). Establishing proper management practices in threatened areas will minimize soil loss and depletion of nutrients due to erosion. As mentioned, slope is a critical and significant factor in the development of erosion-accumulation processes. It does not enter the development of erosion-accumulation processes as a single factor. Based on the results so far, in the future the shape of the relief (convex, concave) and the position on the slope at which the soil probe is augering need to be evaluated as additional factors.

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