SOIL SCIENCE ANNUAL
2025, 76(3), 209899

https://doi.org/10.37501/soilsa/209899

The impact of erosion on the spatial variability of main properties, genesis, and systematic position of soils in the Wieliczka Foothills, southern Poland – a case study from the Bemke Campus area

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Received: 2025-05-06
Accepted: 2025-08-25
Published online: 2025-08-25
Associated editor: Cezary Kabała

Keywords:

Luvisols
Retisols
Cambisols
Soil truncation
Slope morphology
Organic carbon stocks

Abstract

Clay-illuvial soils (PSC, 2019) and their main equivalents in the WRB classification (IUSS Working Group WRB, 2022): Luvisols and Retisols, constitute a fundamental component of Poland's soil cover. Erosional processes, intensified in agricultural areas with diverse relief, lead to substantial transformations of their profiles. As a result of erosional truncation, these soils often become morphologically similar to brown soils (Cambisols). Previous studies from the Carpathian Foothills region indicate a significant presence of both clay-illuvial soils (Luvisols/Retisols), including eroded ones and brown soils (Cambisols). However, distinguishing between these soils can still be problematic. The aim of this study was to assess the impact of erosional processes on the spatial variability of the soil cover in the western part of the Wieliczka Foothills. In particular, the focus was on identifying the main soil types (differentiating between eroded clay-illuvial and brown soils) and relating their properties to slope morphometry and the intensity of erosional transformations. The research was conducted in the western part of the Wieliczka Foothills, on the Bemke Campus in Klecza Dolna. This area is characterized by varied topography, the presence of loess-like covers, and intensive agricultural use. All the soils studied exhibited argik (PSC, 2019) / argic (IUSS Working Group WRB, 2022) illuvial Bt horizons. In the upper, less inclined parts of the slopes, eluvial horizons have been preserved, whereas on steeper slopes the Bt horizons lie directly beneath the humus horizon. The shape of the landforms (long and straight, transfer-type slopes) limited the intensity of erosion, which resulted in the absence of completely eroded soils and the preservation of relatively good quality surface humus horizons, regardless of stage of truncation and slope position. The stocks of organic carbon in the surface layer were higher than in comparable soils of the young-glacial regions of northern Poland. The results indicate the need to expand the research to a larger area of Carpathian Foothills and to undertake more detailed comparative analyses.

1. Introduction

Clay-illuvial soils (PSC, 2019), whose main equivalents in the international WRB soil classification are Luvisols and Retisols (IUSS Working Group WRB, 2022; Kabała et al., 2019; Kabała, 2023), constitute the main component of the soil cover in Poland. The genesis of Luvisols is associated with the process of lessivage, which involves the gravitational translocation, along with percolating groundwater, of the finest fractions (clay) and aluminum and iron hydroxides (Szymański and Skiba, 2007; Świtoniak, 2011; Kabała, 2023). The prevalence of this process results from the dominant climatic conditions in the country—where precipitation exceeds potential evaporation—so a significant part of rainwater infiltrates into the soil, causing the vertical translocation of the above-mentioned components from the surface layer of the soil to deeper horizons (Świtoniak, 2021; Kabała, 2023).

Luvisols, apart from the "common denominator" of illuvial clay accumulation in the Bt horizon, form a very heterogeneous unit in terms of their main properties. Depending on the region where they occur, their texture is determined by the occurrence of various parent rocks and local environmental conditions.

This diversity is divided into several main regions. Luvisols in southern Poland often have a silty texture. In the Carpathian Foothills and Fore-Carpathian region, they formed from non-calcareous loess, known as loess-like silts, which are characterized by a coarser texture compared to typical loess (Uziak, 1962; Zasoński, 1981, 1983; Turski and Witkowska-Walczak, 2004; Szymański et al., 2012; Zaleski, 2012). In this region also clay-illuviated soils with fragipan horizon are found (Szymański et al., 2012).

In the loess areas of the Lublin Upland, Luvisols have a silty or silty-clay texture and are intensively used for agriculture, which usually leads to their erosion and changes in soil structure. Examples of such phenomena have been described in studies conducted, for example, by Paluszek (2001, 2004) or Klimowicz and Uziak (2001). In the Silesian Lowland, Luvisols occur on late Pleistocene loess covers (Glina et al., 2014; Loba et al., 2022). In the southwestern part of Poland, even the loess covers themselves are quite variable—those with a thickness of 2–3 meters are distinguished by lithostratigraphic diversity in the vertical profile, while shallow silty covers, with a thickness of 0.3 to 2.0 meters, are usually non-calcareous and contain admixtures of sandy fractions (Kabała and Marzec, 2010).

The Luvisols of central and northern Poland have clearly different texture — and often greater vertical contrast in this feature.

In the Central and North Poland, the main parent material for clay-illuvial soils is glacial till with a granulometric composition including light loamy sands and sandy loams (A and E horizons) covering more clay-rich material (Bt and C). In the young-glacial area, this material is related to the Vistulian glaciation (e.g., Gajewski et al., 2007; Jaworska et al., 2008; Świtoniak, 2011; Kobierski, 2013). In central Poland, these are often boulder clays deposited during the Saalian glaciation (Warthe/Riss) (Kaczmarek et al., 2007; Kalembasa et al., 2011; Pakuła and Kalembasa, 2013; Paluszek, 2013).

Regardless of the genesis of the parent material and textural variation, clay-illuvial soils are generally considered to be among the most favorable soils for agriculture due to their appropriate water and air properties (Łacek, 1983; Józefaciuk and Józefaciuk, 1999; Paluszek, 2001; Turski and Witkowska-Walczak, 2004; Glina et al., 2014; Sowiński et al., 2023).

Intensive agricultural use exposes them to degradation, especially when they are located on undulating and hilly terrain. These factors lead to very common erosional transformations of described soils — including very strong transformation of their profile structure.

Erosional truncation of these soils leads to partial or even complete disappearance of the eluvial (Et) and even illuvial (Bt) horizons, sometimes exposing the parent rock at the soil surface or just below the humus horizon (Paluszek, 2010; Matecka and Świtoniak, 2020).

Most often, however, erosion processes lead to the total loss of the eluvial horizon (Zaleski, 2012; Kabała and Musztyfaga, 2015) and exposure of Bt horizons directly under the humus horizon (Świtoniak et al., 2016). In such soils humus content decreases (Paluszek, 2010), aggregate structure deteriorates, soil compaction occurs, and crusting may appear (Licznar, 1995; Paluszek, 2001; Nowocień, 2008; Radziuk and Świtoniak, 2022). Additionally, changes in the composition of soil organic matter include, above all, a decrease in humic acid with a simultaneous increase in fulvic acid content (Turski et al., 1987). Material from eroded clay-illuvial soils is transported down the slope, where it accumulates at the foot of slopes and depressions, resulting in the formation of colluvial soils (Turski et al., 1987; Orzechowski et al., 2004; Paluszek, 2010; Świtoniak, 2014; Świtoniak and Bednarek, 2014; Majewski, 2020).

In the past, eroded Luvisols (with Ap-Bt-C profile) were often classified as brown soils (Cambisols in WRB) due to their morphological similarities, especially in agricultural areas (Świtoniak et al., 2016; Kabała, 2023). This problem also appears when comparing older works due to the merging of eroded clay-illuvial soils with brown soils (Niemyska-Łukaszuk et al., 1997; Skiba et al., 2002; Kabała, 2023).

In the meantime, even in the 1930s, it was emphasized that intensive agricultural use contributes to changes in profile morphology by washing away the eluvial horizon, without changing their classification position (Kabała, 2023 after Miklaszewski 1930).

Despite these early observations and later analyses, local distributions and spatial relationships between clay-illuvial and brown soils in Poland were not the subject of detailed studies for a long time. In the second decade of the 21st century were the first attempts made to officially distinguish eroded clay-illuvial soils on a large spatial scale (Kabała 2023 after Białousz and Różycki, 2015; Świtoniak et al. 2016), but precise determination of the properties of such a type/subtype of soils in the Polish Soil Classification required further research (Kabała and Musztyfaga, 2015; Kabała, 2023). As a consequence, 6th edition of the Polish Soil Classification (2019) highlighted as a systematic unit – in the type of clay-illuvial soils, an eroded subtype with an A-Bt-C profile structure was distinguished.

In Poland, the most intense erosion occurs in the south, in loess areas (Licznar, 1995), where water erosion dominates (Prochal, 1973). Erosion is also very common in the highly dissected, young glacial areas of northern Poland (Świtoniak, 2014). Forest-covered mountain slopes effectively limit water erosion, so in natural conditions, this phenomenon practically does not occur in mountain areas (Majewski, 2020). In areas with a loess cover, increased soil erosion leads to a permanent decrease in productivity, which can reach even 30% (Nowocień, 2008).

Methods for measuring the intensity of erosion processes in Poland include both field techniques and mathematical modeling. In field research, sediment traps and collectors are used (Janicki et al., 2006; Smolska, 2010). In loess areas, such as the Lublin Upland and Roztocze, the dynamics of wind processes are monitored with deflameters, splash is studied using collecting cups, the intensity of surface wash is assessed with collectors placed on research plots, and linear erosion caused by heavy rainfall or snowmelt is analyzed by mapping and measuring ephemeral forms created by these processes (Janicki et al., 2006). In addition, isotope methods, including techniques based on the analysis of 137Cs activity, are used to measure erosion and accumulation (Yang et al., 2006; Janicki et al., 2006; Poręba, 2008; Kobierski, 2013; Loba et al., 2021; Loba et al., 2022).

For younger sediments, the luminescence dating (OSL) method is used (Poręba et al., 2015; Poręba et al., 2019). To assess soil erosion on a larger scale, mathematical models have been developed, including USLE (Universal Soil Loss Equation), designed to estimate annual erosion rates based on an equation (Piotrowska, 1998; Gobin et al., 2003; Kowalczyk and Twardy, 2012; Wężyk et al., 2012; Radziuk and Świtoniak, 2021).

Currently, these techniques are combined with GIS modeling, allowing for the creation of maps showing the erosion risk of agricultural soils, to determine the magnitude of current and potential erosion (Wężyk et al., 2012). One of the simplest methods to determine the degree and extent of erosional changes in the soil cover is also to assess the degree of truncation or accumulation of the soil profile by slope processes (Sinkiewicz, 1998; Klimowicz and Uziak, 2001; Świtoniak, 2014). This method was used in the presented research.

The aim of the present study is to determine the impact of erosional transformations on the soil cover of the western part of the Wieliczka Foothills, using the example of the Bemke Campus area. To achieve this aim, the following research tasks were carried out:

- description of spatial variability of soils along slopes exposed to intensive and long-lasting slope processes—both in terms of their main properties (including organic carbon resources), genesis, and systematic position;
- determination of the relationships between morphometric indicators of slopes and the degree of erosional transformation;
- assessment of the quality of the studied soils, with particular emphasis on the degree of development and properties of their humus horizons.

2. Study area and methods

The study area is located within the Wieliczka Foothills (Fig. 1) being part of the Outer Western Carpathians (Kondracki, 2009), situated between the valleys of the Skawa and Raba rivers. This mesoregion is characterized by a varied terrain and intensive agricultural use, supported by favorable mesoclimatic conditions (Balon et al., 2022).

According to the Köppen-Geiger climate classification, the study area is located in a humid temperate climate zone with moderately warm summers (Kottek et al., 2006). The annual air temperature (1991–2020) is about 8.5°C, while the average annual precipitation is around 850 mm, with most rainfall occurring in the summer (Tomczyk and Bednorz, 2022). The humid period (when precipitation exceeds potential evaporation) lasts the whole year, resulting in a percolating soil-water regime in soil pedons with good natural drainage.

The substrate of the mesoregion is mainly built of Outer Carpathian flysch rocks—sandstones and shales of the Silesian series, including black shales with interlayers of sandstones and siderites (the Wierzówka Beds), shales and sandstones (the Lgota Beds) (Ryłko and Paul, 2013). The terrain is dominated by relief with varied elevation, with differences reaching up to 157 meters (Bajgier, 1992). There are numerous hills and ridges dissected by ravines and valleys, which are traces of the retreat of the ice sheet, while in the valleys, materials of fluvial accumulation have accumulated (Ryłko and Paul, 2013). In this area, landslides are common, most often frontal ones (Bajgier, 1992). According to the geological map at a scale of 1:50,000, the study area is covered by loess and loess-like silts. Nearby, there is also the Klecza Dolna–Łękawica–Dąbrówka fault, which is part of the so-called major fault zone of the Skawa valley (Cieszkowski et al., 2006). This fault zone caused the truncation of the upper part of the Silesian nappe from the western side (Ryłko and Paul, 2013).

The research was conducted in the western part of the foothills, on the Bemke Campus located in Klecza Dolna (Fig. 1). For detailed research, two study sites were designated – a northern (N) and a southern (S) site, covering areas of 3.5 ha and 7.2 ha, respectively. Both sites are located on the edge of the foothills, including the slopes of the Skawa river valley. This location determines the main terrain features—on both sites, there are distinct slopes descending westward from an elevation of about 295 to 270 m a.s.l. The slope inclination ranges up to 10°. Due to the considerable extent of the landforms, the shape of the slopes is approximately straight. Along the western edge of the southern site, strong anthropogenic modifications of the slopes are visible, resulting from earlier leveling works.

In the examined fragment of the Wieliczka Foothills, a total of 5 soil pits and 16 auger holes were made during the fieldwork in July 2023. Soil pits and auger holes were located at characteristic points of the terrain so that they would represent the entire soil cover of the studied area. One profile was located within arable land, one in a park, while the remaining ones were grassland (Fig. 2).

From the material taken from the surface horizons of auger borings and all genetic horizons from the soil pits, laboratory analyses were performed, including:

- determination of particle size distribution using the Bouyoucos areometric method, modified by Casagrande and Prószyński;
- soil organic carbon (OC) and total nitrogen (Nt) content were determined by dry combustion using a Vario Macro Cube macroanalyzer;
- pH determination by the potentiometric method.

In addition, exchangeable cations were determined using the ammonium acetate method in accordance with the guidelines of the International Soil Reference and Information Center (Reeuwijk, 2002). Soil color was described using the Munsell Soil Color Charts (2000).

Undisturbed soil samples were taken from humus horizons using a metal rings with volume of 100 cm^3. These samples were used to determine bulk density (BD).

The symbols/names of diagnostic horizons and systematic position were determined according to the sixth edition of the Polish Soil Classification (PSC, 2019) and WRB (IUSS Working Group WRB, 2022). Names of soil units in English were cited according to the proposal by Kabała et al. (2019).

Organic carbon stocks (SOC, $kg \cdot m^{-2}$) were calculated using equation (1):

$$SOCs = [SOC \cdot BD \cdot t \cdot (1 - SK\%)], \quad (1)$$

where:

SOC – organic carbon content ($g \cdot kg^{-1}$);
BD – bulk density ($g \cdot cm^{-3}$);
t – thickness of the horizon (m);
SK – content of the skeletal fraction $\phi > 2.0$ mm (determined by sieving).

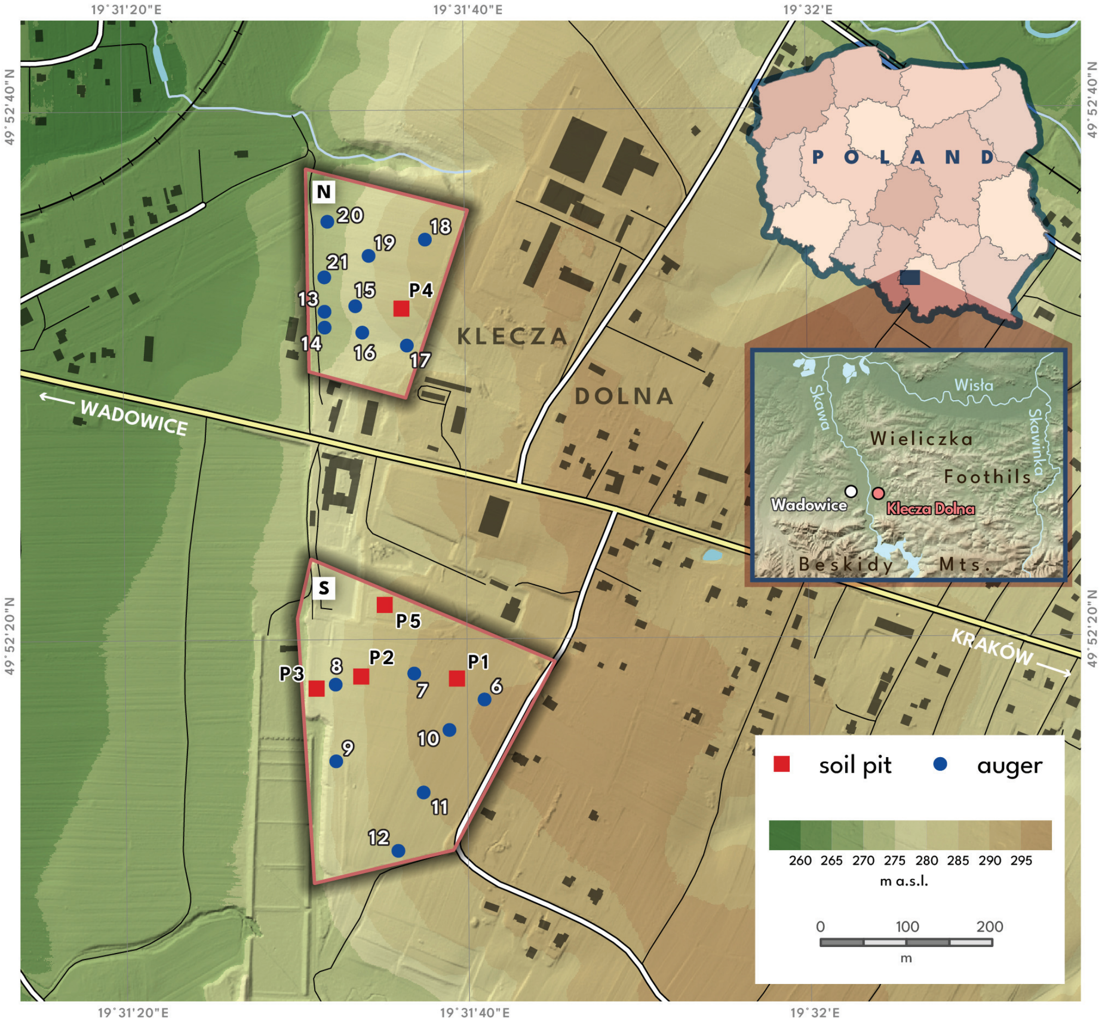

Fig. 1. Location of the study sites

The slope inclination and shape models were conducted based on a digital elevation model provided by the Head Office of Geodesy and Cartography (GUGiK). DEM data was acquired via airborne LiDAR on June 6th, 2024, and the model has a spatial resolution of 1 m.

The Normalised Difference Vegetation Index (NDVI) for the study area was calculated using cloud-free Sentinel-2 satellite imagery covering the different phases of the growing season: May 18th, June 15th, and July 10th. The red (B04) and near-infrared (B08) bands, both of which have 10 m spatial resolution, were used. Standard algebraic operations for NDVI were followed: NDVI = (NIR-Red) / (NIR+Red), as proposed by Jackson and Huete (1991).

Both slope analyses and vegetation index calculations were conducted using ArcGIS Pro v.3.2.1 software by Esri Inc.

3. Results

A common feature of the studied soils is the presence of diagnostic argik horizons (WRB: argic), starting at depths of up to 100 cm from the surface and characterized by an increase in clay content (Tab. 1), a significant amount of clay coatings on the surfaces of aggregates, relatively high bulk density (Tab. 2), high saturation of the sorption complex with base cations, and high cation exchange activity of the clay fraction (Tab. 3).

The humus horizons are generally well developed and rich in organic carbon, and due to agrotechnical treatments, reach at least 30 cm in thickness; however, they do not meet the criteria for the dark color of diagnostic mollik (PSC 2019) / mollic horizons (IUSS Working Group WRB, 2022).

Profile 1 is located in the upper part of the slope (site S), in an area used agriculturally as arable land (Fig. 2). In this soil, the presence of eluvial (Et) and argik (PSC 2019) / argic (IUSS Working Group WRB, 2022) Bt horizons was found — both with clear signs of moderately expressed water stagnation. The transition between the eluviation and illuviation horizons has a tongue-like pattern. Accordingly, this soil was classified as stagnogleyic tonguing clay illuvial soil (PSC, 2019) or Eutric Stagnic Retisol (IUSS Working Group WRB, 2022). Soils with a similar genetic horizons sequence also occurred in auger-holes 9 and 21.

Profiles 2 and 4 are very similar in terms of morphology (Fig. 2). The first of these is in the middle part of the slope (site S), the second at the shoulder of the slope (site N). Both are used

Table 1
Texture of the studied soils

Genetic horizon	Depth [cm]	Sand 2.0–0.5 mm	Silt 0.05–0.002 mm	Clay < 0.002 mm	Textural group SSSP (2008)	WRB (2022)
		[%]				
P1 – Stagnic clay-illuvial soil Eutric Stagnic RETISOL (Siltic, Aric, Cutanic, Ochric)						
Ap	0–25	29	64	7	pyg	SiL
Et	25–30	26	64	10	pyg	SiL
E/B	30–50	18	67	15	pyi	SiL
Btg	50–90	23	62	15	pyi	SiL
BC	90–110	22	60	18	pyi	SiL
P2 – Eroded humic clay-illuvial soil (stagnic) Stagnic LUVISOL (Siltic, Aric, Cutanic, Ochric)						
Ah	0–10	23	69	8	pyg	SiL
Ap	10–38	26	65	9	pyg	SiL
Btg	38–90	32	50	18	pyi	SiL
BC	90–110	29	54	17	pyi	SiL
P3 – Humic clay-illuvial soil (covered) Haplic LUVISOL (Siltic, Aric, Cutanic, Humic, Solimovic)						
Ah	0–10	31	60	9	pyg	SiL
A1	10–50	32	62	6	pyg	SiL
A2	50–70	32	59	9	pyg	SiL
A/E	70–100/80	31	59	10	pyg	SiL
Btg	100/80–120	28	56	16	pyi	SiL
P4 – Eroded humic clay-illuvial soil Haplic LUVISOL (Siltic, Aric, Cutanic, Ochric)						
Ah	0–10	30	64	6	pyg	SiL
Ap	10–30	28	63	9	pyg	SiL
Btg	30–70	24	60	16	pyi	SiL
P5 – Humic stagnic clay-illuvial soil Stagnic RETISOL (Siltic, Cutanic, Ochric)						
A	0–10	28	61	11	pyg	SiL
AE	10–40	27	63	10	pyg	SiL
E/B	40–70	35	56	9	pyg	SiL
Btg	70–150	25	58	17	pyi	SiL

Explanations: pyg – loamy silt, pyi – clayey silt, SiL – silty loam

as meadow. In these soils directly below the humus horizon lies the argic horizon with weakly developed features connected with water stagnation (Btg). Described soils resemble brown soils (WRB - Cambisols) in appearance, but due to the presence of a diagnostic argik/argic horizon and the absence of an eluvial horizon, the soil was classified as eroded humic clay-illuvial soils (PSC, 2019) or Haplic/Stagnic Luvisol (IUSS Working Group WRB, 2022). The augers (Tab. 4) confirmed the dominance of soils with Ap-Btg-C profiles in both study sites.

In the lower part of the slope of site S, in an area also covered by meadow vegetation, profile 3 was located (Fig. 2). It represents a humic clay-illuvial soil (PSC, 2019) or Luvisol (IUSS Working Group WRB, 2022) overlain by a colluvial (called solimovic in WRB) humic material mixed with a primary humus horizon with a thickness of 70 cm. At a depth of 70–100 cm, there is a mixed humus-eluvial horizon, and deeper, an illuvial Btg horizon. The presence of colluvial/solimovic material with a thickness of at least 50 cm was also noted in auger-holes 14, 16, 17, and 20 (Tab. 4).

Table 2
Chemical and physicochemical properties of the studied soils

Genetic horizon	Depth [cm]	OC	Nt	C/N	pH		Munsell colour		Bulk density (BD)	Carbon stocks
		[%]			H_2O	KCl	dry	wet	[g·cm^{-3}]	[kg·m^{-2}]
P1 – Stagnic clay-illuvial soil Eutric Stagnic RETISOL (Siltic, Aric, Cutanic, Ochric)										
Ap	0–25	1.45	0.137	11	5.3	4.5	10YR 7/3	10YR 5/3	1.44	5.220
Et	25–30	0.59	0.071	–	5.9	4.6	10YR 8/3	10YR 6/3	1.51	0.445
E/B	30–50	0.24	0.033	–	5.9	4.4	10YR 8/2	10YR 7/3	1.53	0.734
Btg	50–90	0.08	0.019	–	5.1	3.7	10YR 8/4	10YR 6/6	1.58	0.506
BC	90–(110)	0.08	0.015	–	5.5	3.8	10YR 8/4	10YR 6/6	1.54	0.123
									Total:	**7.029**
P2 – Eroded humic clay-illuvial soil (stagnic) Stagnic LUVISOL (Siltic, Aric, Cutanic, Ochric)										
Ah	0–10	1.68	0.163	10	5.6	4.5	10YR 6/3	10YR 4/2	1.40	2.352
Ap	10–38	0.89	0.104	9	5.7	4.4	10YR 7/4	10YR 5/4	1.52	3.788
Btg	38–90	0.14	0.028	–	5.7	4.0	10YR 8/4	10YR 6/6	1.57	1.143
BC	90–(110)	0.10	0.023	–	5.2	3.8	10YR 8/4	10YR 5/6	1.57	0.157
									Total:	**7.440**
P3 – Humic clay-illuvial soil (covered) Haplic LUVISOL (Siltic, Aric, Cutanic, Humic, Solimovic)										
Ah	0–10	2.05	0.20	10	5.6	4.7	10YR 6/2	10YR 4/2	1.36	2.788
A1	10–50	0.75	0.08	9	6.2	4.8	10YR 7/3	10YR 5/4	1.59	4.770
A2	50–70	0.60	0.08	7	6.1	4.6	10YR 8/3	10YR 6/4	1.45	1.740
A/E	70–100/80	0.30	0.03	10	6.1	4.4	10YR 8/2	10YR 6/4	1.50	0.900
Btg	100/80–(120)	0.15	0.03	–	5.7	4.1	10YR 8/4	10YR 6/6	1.55	0.233
									Total:	**10.431**
P4 – Eroded humic clay-illuvial soil Haplic LUVISOL (Siltic, Aric, Cutanic, Ochric)										
Ah	0–10	1.92	0.200	10	5.5	4.3	10YR 7/2	10YR 5/2	1.45	2.784
Ap	10–30	1.26	0.141	9	5.7	4.4	10YR 7/3	10YR 5/3	1.51	3.805
Btg	30–(70)	0.21	0.037	–	6.5	4.5	10YR 8/4	10YR 6/7	1.66	1.394
									Total:	**7.984**
P5 – Humic stagnic clay-illuvial soil Stagnic RETISOL (Siltic, Cutanic, Ochric)										
A	0–10	0.91	0.066	14	4.6	4.0	10YR 6/2	10YR 4/3	1.26	1.147
AE	10–40	0.57	0.065	9	4.7	4.0	10YR 7/3	10YR 5/3	1.4	2.394
E/B	40–70	0.21	0.025	–	4.8	3.9	10YR 8/3	10YR 6/4	1.42	0.895
Btg	70–(150)	0.11	0.032		5.0	3.8	10YR 8/6	10YR 6/8	1.57	1.382
									Total:	**5.817**

Table 3
Properties of the cation exchange complex of the studied soils

Genetic horizon	Depth [cm]	TEB	HA	CEC	CECclay	BS [%]
		[cmol(+)×kg $^{-1}$]				
P1 – Stagnic clay-illuvial soil Eutric Stagnic RETISOL (Siltic, Aric, Cutanic, Ochric)						
Ap	0–25	4.757	5.037	9.794	46.7	49
Et	25–30	3.427	3.356	6.783	41.3	51
E/B	30–50	4.439	2.376	6.815	38.2	65
Btg	50–90	5.899	3.991	9.890	63.5	60
BC	90–(110)	8.143	2.635	10.778	57.9	76
P2 – Eroded humic clay-illuvial soil (stagnic) Stagnic LUVISOL (Siltic, Aric, Cutanic, Ochric)						
Ah	0–10	5.324	4.858	10.182	32.8	52
Ap	10–38	4.424	4.022	8.446	49.3	52
Btg	38–90	6.114	3.212	9.326	48.3	66
BC	90–(110)	5.249	4.047	9.296	52.0	56
P3 – Humic clay-illuvial soil (covered) Haplic LUVISOL (Siltic, Aric, Cutanic, Humic, Solimovic)						
Ah	0–10	7.233	5.152	12.385	35.1	58
A1	10–50	6.594	3.302	9.896	108.7	67
A2	50–70	4.101	3.371	7.472	53.0	55
A/E	70–100/80	3.920	2.771	6.691	53.4	59
Btg	100–80–(120)	5.835	2.738	8.573	49.4	68
P4 – Eroded humic clay-illuvial soil Haplic LUVISOL (Siltic, Aric, Cutanic, Ochric)						
Ah	0–10	6.463	5.543	12.006	56.1	54
Ap	10–30	5.812	4.297	10.109	49.3	57
Btg	30–(70)	6.77	2.133	8.903	49.7	52
P5 – Humic stagnic clay-illuvial soil Stagnic RETISOL (Siltic, Cutanic, Ochric)						
A	0–10	0.387	7.201	7.588	31.8	5
AE	10–40	0.373	6.151	6.524	39.6	6
E/B	40–70	0.851	4.631	5.482	50.4	15
Btg	70–(150)	4.447	4.177	8.624	47.8	52

TEB – total exchangeable bases; HA – potential hydrolytic acidity; CEC – cation exchange capacity, CECclay – CEC of the clay; BS – base saturation

In augers 14 and 17, these were deep solimovic material (to the bottom of the boring, more than 100 cm), in points 16 and 20, under the solimovic material at depths of 90 and 60 cm, respectively, Btg horizons were recorded, so these soils were classified as clay-illuvial soils. Despite the clearly humic character of the solimovic material, only in profile 16 its color was dark enough to meet the criteria of a mollik/mollic horizon and the soil was classified as chernozemic colluvial soil (PSC, 2019) or Phaeozem (Solimovic) – according to WRB (IUSS Working Group WRB, 2022).

Profile 5 is also located in the upper part of the slope, currently used as a park, previously as a forest (Fig. 2). This is a humic stagnic clay-illuvial soil (PSC, 2019) or Stagnic Retisol with traces of anthropogenic transformation/disturbances in upper 30 cm (IUSS Working Group WRB, 2022).

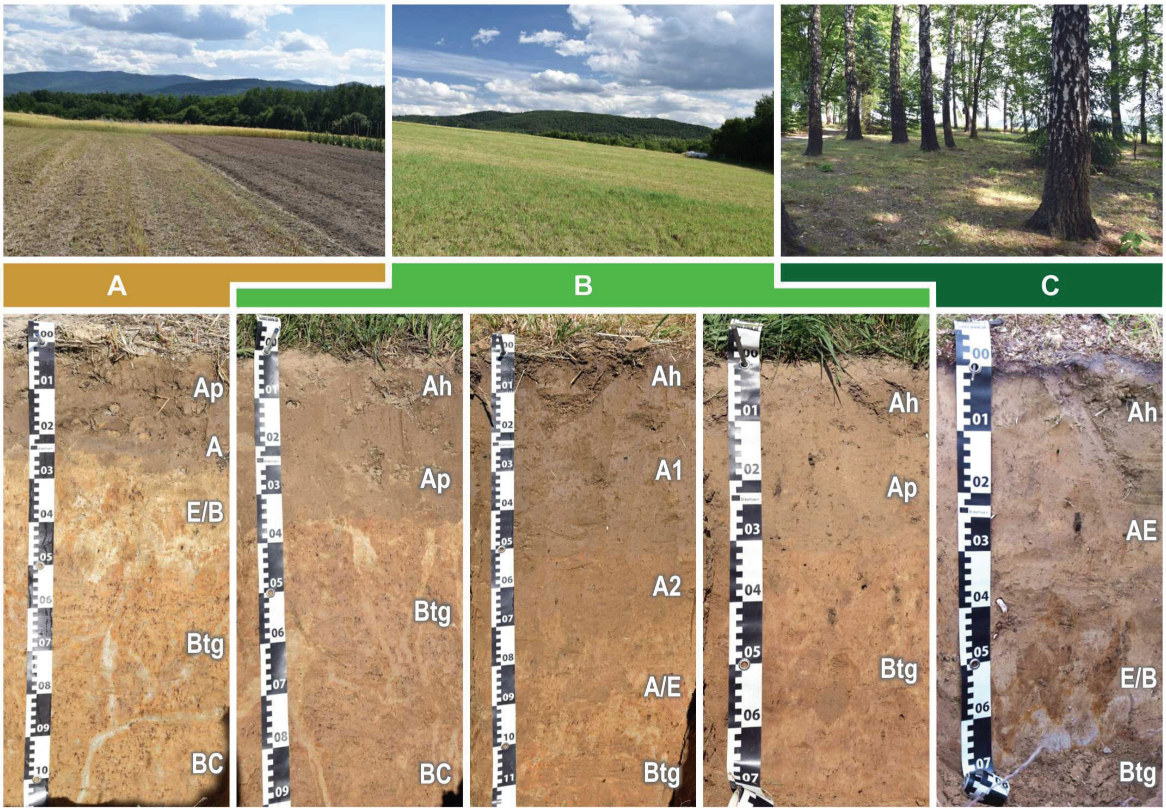

Fig. 2. Land use and morphology of the studied soils (A – arable field, B – meadow, C – park)

Table 4
Basic characteristics of surface horizons and the genetic horizon sequence investigated in the auger-holes

Auger-hole	Depth of humus horizon [cm]	Sand 2.0–0,5 mm [%]	Silt 0.05–0.002 mm	Clay < 0.002 mm	OC	N_t	pH H_2O	pH KCl	C/N	Munsell colour dry	Munsell colour wet	Sequence of horizons
6	0-30	27	66	7	1.44	0.131	5.9	4.6	11	10YR 7/2	10YR 5/2	Ap-Etg-Btg
7	0-30	28	67	5	1.35	0.136	6.1	5.0	10	10YR 7/2	10YR 4/3	Ap-Btg-C
8	0-30	30	58	12	0.79	0.090	6.2	4.8	9	10YR 7/3	10YR 4/5	Ap-Btg-C
9	0-30	32	57	11	0.68	0.076	6.0	4.7	9	10YR 7/4	10YR 5/4	Ap-Et-Btg-C
10	0-40	28	66	6	1.18	0.117	6.5	5.5	10	10YR 7/2	10YR 4/3	Ap-Btg-C
11	0-30	24	70	6	1.43	0.140	6.6	5.7	10	10YR 7/2	10YR 4/3	Ap-Btg-C
12	0-30	22	67	11	0.91	0.100	6.6	5.4	9	10YR 7/3	10YR 5/4	Ap-Btg-C
13	0-30	38	53	9	1.82	0.141	6.0	5.0	13	10YR 7/2	10YR 5/2	Ap-Btg-C
14	0-90	30	61	9	1.38	0.141	6.3	5.4	10	10YR 7/2	10YR 5/2	A-A2-A3
15	0-30	34	57	9	0.98	0.111	5.9	4.6	9	10YR 6/4	10YR 4/4	Ap-Btg-C
16	0-35	39	56	5	2.40	0.167	6.2	5.2	14	10YR 5/2	10YR 3/1	Ap-A-Btg
17	0-60	32	62	6	1.78	0.176	6.7	5.9	10	10YR 6/2	10YR 4/2	A-A2-A3
18	0-15	25	67	8	1.47	0.173	5.6	4.5	8	10YR 7/2	10YR 5/2	Ap-Bt-C
19	0-30	31	59	10	1.06	0.119	5.6	4.3	9	10YR 7/3	10YR 5/5	Ap-Btg-C
20	0-50	37	56	7	1.06	0.123	6.0	4.8	9	10YR 7/2	10YR 5/4	Ap-A-Et-Btg
21	0-10	44	50	6	1.06	0.113	6.7	5.6	9	10YR 7/2	10YR 4/3	Ap-Et-Btg-C

According to the criteria adopted in the WRB (IUSS Working Group WRB, 2022), in all studied clay-illuvial soils the key role in determining the systematic position was played by the argik/argic illuvial horizons. If they were characterized by tongue-like within upper part soils represents Retisols, in other cases (with lack of tonguing) classified as Luvisols due to a high degree of saturation of the sorption complex with base cations as well as high clay activity – as presented in Table 3.

The dominant fraction in all material taken from profiles (Tab. 1) and borings (Tab. 4) is the silt fraction. In the two first profiles, in the upper horizons (humus and, in the case of the first profile, the eluvial horizon), the texture is silty loam (pyg – SSSP, 2008), while deeper, it is silty clay (pyi, SSSP, 2008). The upper part of profile 3, consisting mainly of colluvial/solimovic material, is characterized by silty loam texture, which may indicate that this is material derived from the humus and eluvial horizons of soils originally developed in the higher parts of the slope.

In addition, the share of the finest clay fraction (<0.002 mm) increases with depth which indicates the lessivage process. In profiles located in the upper parts of the slope: in profile 1, from 7% in the Ap horizon to 15% in the Btg horizon, and in profile 2, from 8% in the Ap1 horizon to 18% in the Btg horizon. Profile 3 with colluvial material is characterized by a lower clay fraction content, with higher content observed in the buried part in the Btg horizon at 100 cm depth.

4. Discussion

The conducted research on the soil cover confirmed the absolute dominance of clay-illuvial soils (PSC, 2019) or Luvisols/Retisols (IUSS Working Group WRB, 2022) within investigated area. In the upper, linear (straight) parts of the less inclined slopes, apart from the Bt horizons, the eluvial horizons have also been preserved, making the classification of these soils straightforward.

Already in the second half of the 20th century, during large-scale cartographic fieldwork, these soils were classified as clay-illuviated soils (then called pseudo-podzolic soils)—which is reflected by the symbol "A" used on maps (Fig. 3). Within the more steeply inclined slopes, especially those that are slightly convex, Bt horizons lie directly under humus horizons, resulting in morphological similarity of these soils to brown soils (PSC, 2019) or Cambisols (IUSS Working Group WRB, 2022). For this reason, on soil-agricultural maps, significant areas of soils located within the slopes of the Skawa valley were marked with the symbol "Bw", originally used by classifiers to indicate the presence of leached brown soils. The "leaching" in the studied area results from the non-calcareous nature of the loess-like deposits that constitute the parent rock of the described soils.

Classifying soils with an A-B-C horizon sequence (with B horizons just under the humus horizon) as brown soils (Cambisols) can be found in some scientific works on the Wieliczka Foothills (e.g., Niemyska-Łukaszuk et al., 1997; Drużkowski 2001).

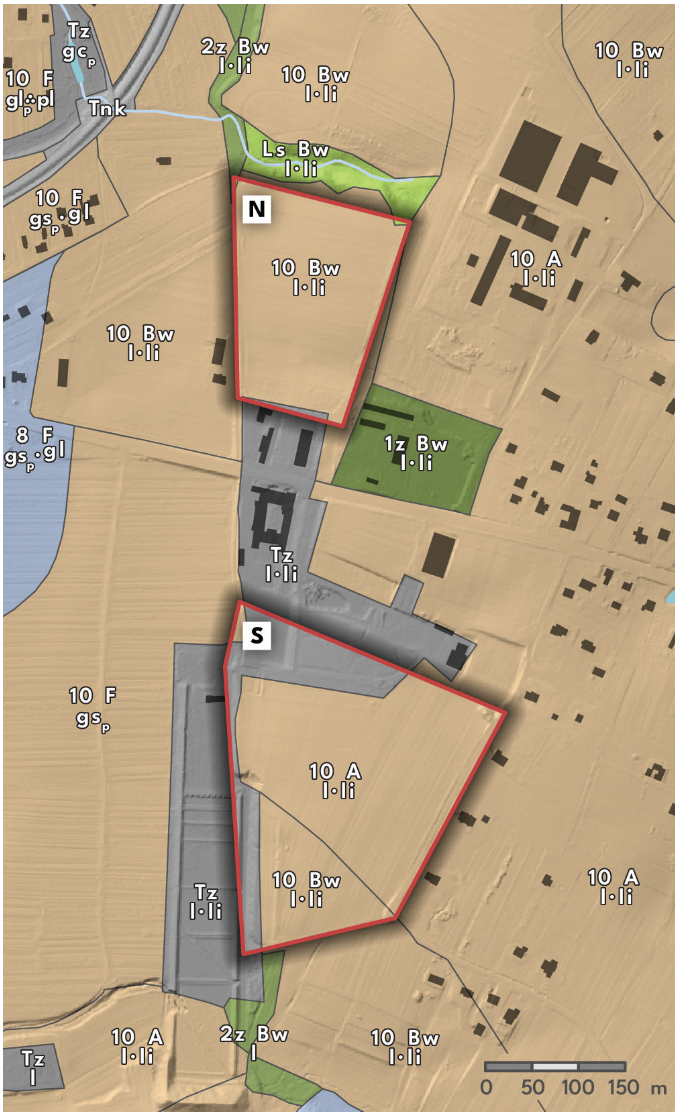

Fig. 3. Soil-agricultural map of the study area:

Land use:
Arable lands
8 – strong cereal-pasture complex (blue)
10 – mountain wheat complex (beige)
Meadows and pastures
1z – very good and good (dark green)
2z – average (green)
Other land uses
Tz – built-up area (grey)
Ls – forest (light green)
Soils:
A – pseudo-podzolic soils (Luvisols)
Bw – leached brown soils (Cambisols)
F – alluvial soils (Fluvisols)
Texture:
l – loess
li – loess clay
gsp – medium-heavy loam with admixture of silt

At the same time, many authors emphasize the widespread occurrence throughout the Carpathian Foothills of the lessivage process and accompanying by stagnation of water in soils formed from loess-like silts (e.g., Uziak, 1962; Skiba, 1995; Szymański et al., 2011, 2012, 2017; Zaleski, 2012; Kabała, 2023), which has been confirmed by detailed micromorphological studies (Zasoński, 1974, 1975, 1979, 1980, 1983). Some authors also point out that brown soils (Cambisols) in the foothill zone may rather occur as young soils developed from colluvial material or from the weathered Carpathian flysch (Zasoński, 1993; Skiba et al., 2002; Zaleski, 2012; Musielok, 2022), while a large share of soils with an A-B-C morphology are actually clay-illuvial soils (Luvisols) eroded by slope processes (e.g., Uziak, 1962; Zasoński, 1989; Zaleski, 2012). In administrative reports, such as environmental protection programs, information about soil cover still lists brown soils (Cambisols) as its basic component, without considering the erosional origin of soils with the A-B-C morphology (Wadowice County Council, 2015).

The vertical differentiation of the clay fraction content shows depletion of the surface A horizons in this fraction. This vertical textural differentiation by itself is not conclusive evidence for pedogenic clay translocation. Due to deep leaching, the base of the solum was not reached in the pits, so it cannot be established whether the B horizons have a clearly increased clay content compared to the parent rocks. Moreover, loess-like deposits are characterized by a lithogenic vertical variability of fine fractions (e.g., Grabowski, 1999) and may be transformed by various phases of older stages of pedogenesis to considerable depths (e.g., Mroczek and Rodzik 2011; Krawczyk et al., 2017). Nevertheless, In the case of the analyzed area, the illuvial origin of the B horizons is beyond doubt, even without the use of costly and time-consuming micromorphological analyses. During fieldwork, in all B horizons, a significant number of clay coatings were observed on the surfaces of soil aggregates. Moreover, in the spatial (catenary) perspective, B horizons continue along the slopes: from non-eroded clay-illuvial soils (Luvisols/Retisols) with E horizons on flat plateaus, through more shallowly lying B horizons directly under humus horizons in soils located on slopes, to the lowest-lying clay-illuvial soils (Luvisols), where they are buried under colluvial deposits.

Thus, the problems with classifying soils with the A-B-C profile are similar to those observed earlier in the Polish Lowland (Świtoniak et al., 2016). According to the adopted classification of the degree of erosion (Świtoniak, 2014), the studied clay-illuvial soils of the Wieliczka Foothills represent a medium degree of erosion, where remnants of the eluvial material, mixed by agrotechnical operations and slope processes, are still present in the humus horizons. This is evidenced by the lower clay content in the Ah, A, and Ap horizons compared to the Bt horizons at both analyzed sites.

It is worth noting that despite the considerable slope inclination in the analyzed area, no strongly or completely eroded soils were recorded. In other regions of Poland soil erosion phenomena often results in a reduction in soil cover thickness up to its complete disappearance (Paluszek and Żembrowski, 2008). In the case of Luvisols, their complete erosion can lead to transformation into poorly developed Regosols (Matecka and Świtoniak, 2020) but within investigated area such soils were not observed at all. This is probably due to the specific landform prevailing in the investigated region. The shape of the slopes at both study sites is, for the most part, approximately straight—the studied area lies in a "transfer" zone of extensive, steep (up to 10°) but straight slopes separating the plateau of the foothills in the east from the Skawa valley in the west (Fig. 4 and Fig. 5). The presence of surface slope deposits therefore prevents deep truncation of the soils. Meanwhile, in young glacial areas, where there is a significant share of convex slopes referring to small-area but oval-shaped hills, the share of strongly and completely eroded soils is significant. At the same time, colluvial soils often occur in depressions (Matecka and Świtoniak, 2020; Radziuk and Świtoniak, 2022).

A specific feature of the studied area is not only the relatively small extend of strongly eroded but also colluvial soils. Colluvium (solimovic material – WRB 2022) occur mainly in the western part of the study area as a several dozen-centimeter layer covering Luvisols. This material is retained not because of the landform itself—this is not yet the lowest, aggradational part of the Skawa valley slopes. In the case of study site S, the steepest slope fragments are even below the accumulation zone of the studied colluvial soils (Fig. 4). In the analyzed area, a field margin crossing the slopes, likely created relatively recently (several hundred or several dozen years ago) and acts as a sediment trap. Colluvial deposits of considerable thickness were recorded only in auger-holes 14 and 17 (Fig. 1, Tab. 4) within a small, erosionally incised section perpendicular to the main slope, located in the southern part of site N. The study sites do not include the lowest parts of the valley slopes, so it can be expected that a significant portion of the eroded material has been accumulated outside the studied area.

Erosional processes lead to the deterioration of physical and chemical properties of soils, especially the quality of humus horizons (e.g., Turski et al., 1987; Van Oost et al., 2003; Paluszek and Żembrowski, 2008; Martinez-Casasnovas and Ramos, 2009; Rybicki, 2010; Žížala et al., 2019). A decrease in organic carbon content in these horizons indicates the intensity of erosion and the degree of humus loss (Orzechowski et al., 2004). Similar trends were observed in studies conducted on a slope in the Sandomierz Upland, where the lowest organic carbon content was found in the most eroded soils, located on slopes with an inclination greater than 15% (Rybicki, 2010). In the case of the studied soil cover, slope processes led to a significant shallowing of most soils and, in some cases, to the accumulation of colluvial material over the original pedons. However, the rate of these processes must have been strongly limited, as the quality of humus horizons in eroded soils does not show significant deterioration or differentiation within individual parts of the slopes. This spatial uniformity in the productive quality of the studied soils (regardless of the depth of the Bt horizon top) is reflected in the analysis of the NDVI index from different stages of the vegetation period for site N (site S is used differently – arable field/grassland), whose values do not show significant spatial differences or correlation with the degree of clay-illuvial soils shallowing (Fig. 6).

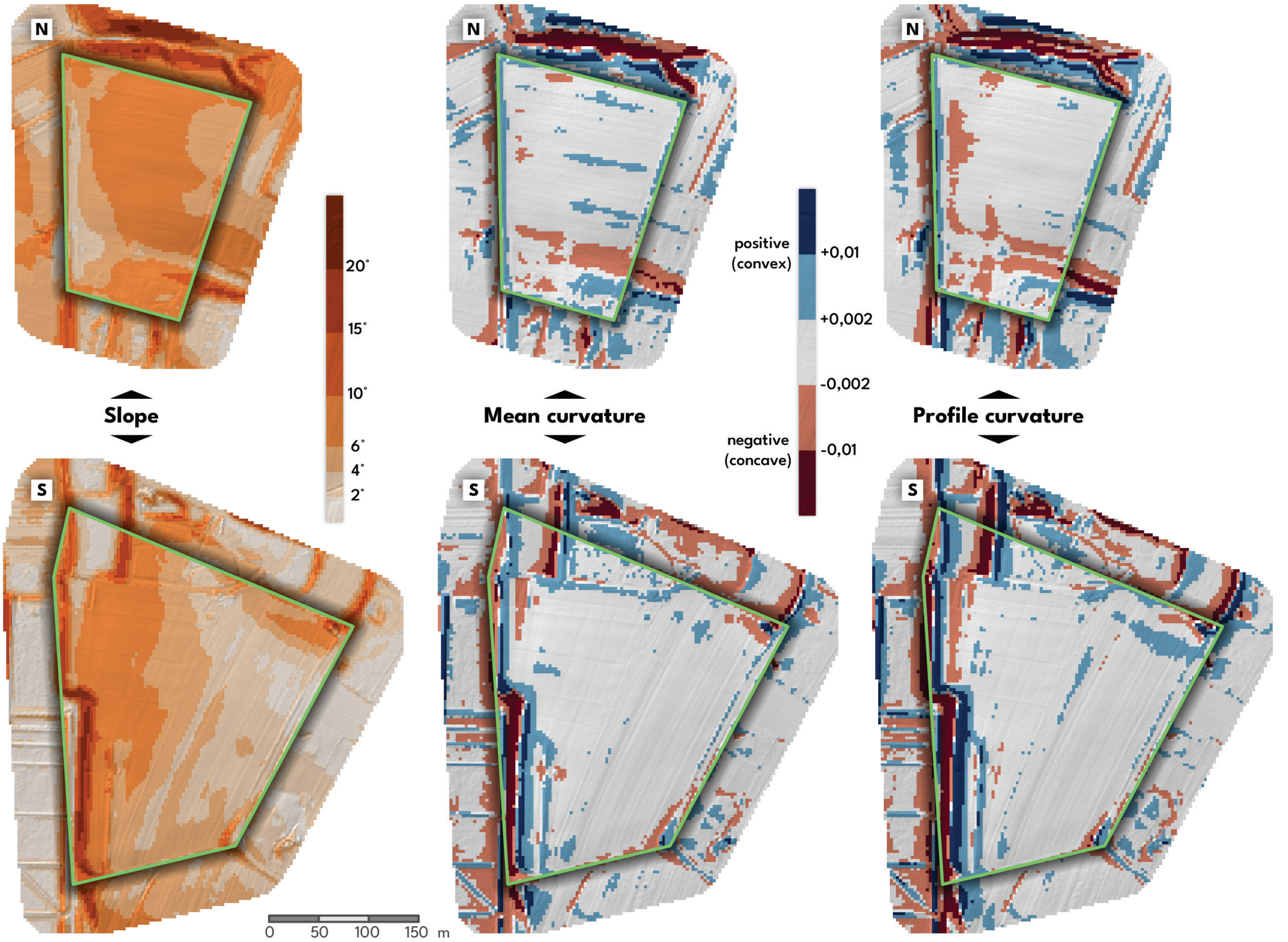

Fig. 4. Slope inclination and shape of both study sites

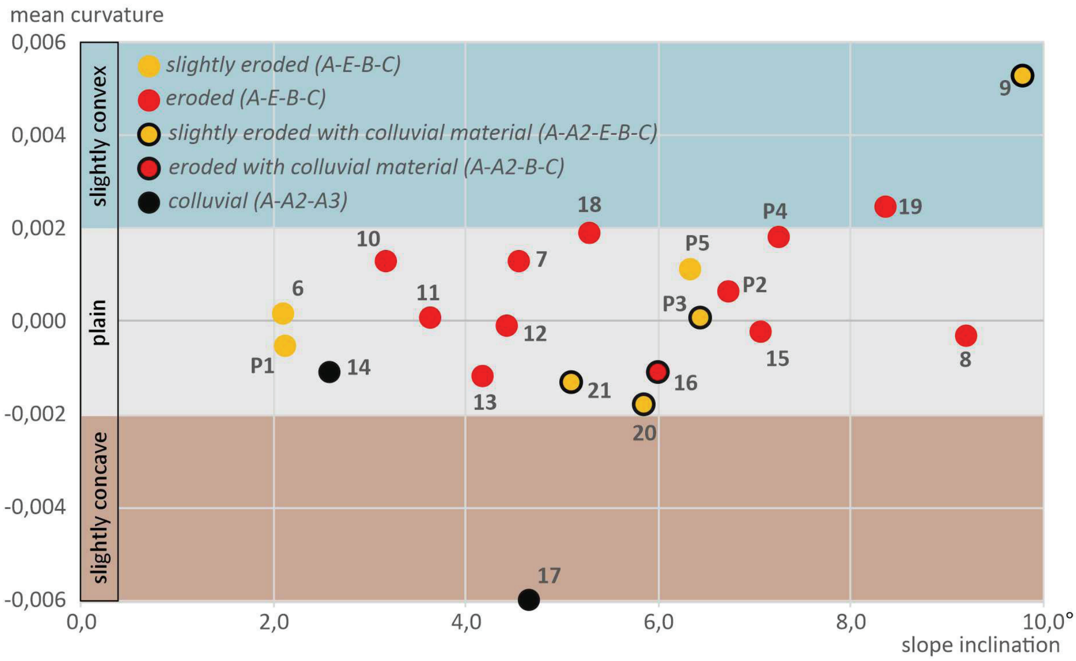

Fig. 5. Morphometric characteristics (inclination and shape) of slopes at the locations of the studied soils

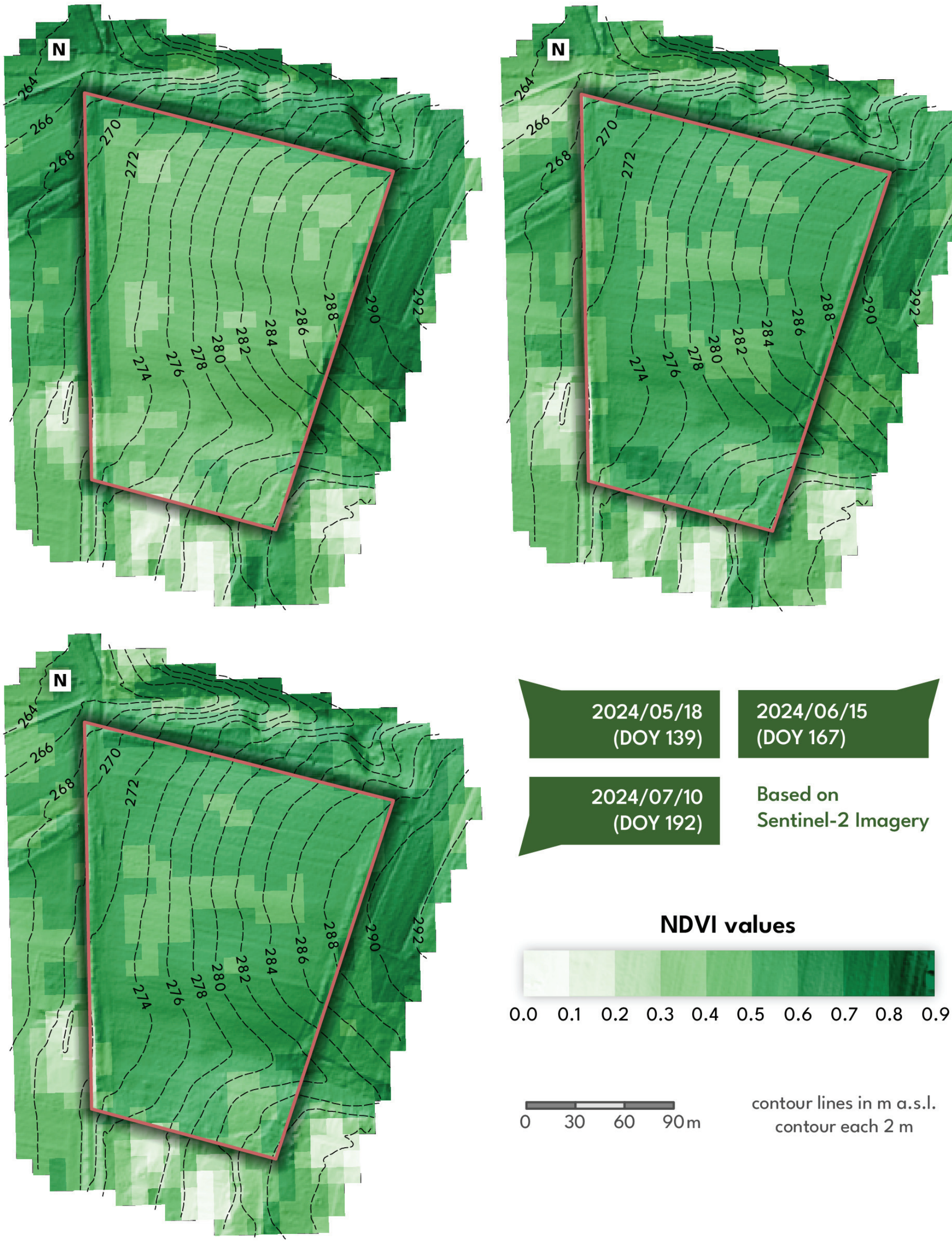

Fig. 6. NDVI index for study site N – year 2024

This situation may also result from the aforementioned location of the studied soils in a straight (not convex) slope transfer zone, where the loss of humus material is compensated by material with similar properties and content of humus from the upper parts of the slope. All the studied humus horizons of agriculturally used soils (P1–P4) showed a favorable subangular blocky and stable aggregate structure and had considerable (in case of clay-illuvial soils / Luvisols) organic carbon content, exceeding 1% on average in the 0–30 cm layer (Tab. 2). For the analyzed grasslands (P1–P4), up to 10 cm depth, this partly results from the current accumulation of carbon from the decomposition of grass roots. Nevertheless, in the deeper zone of humus horizons (10–30 cm), formerly arable layers, the OC content does not drop below 0.75%. Previous studies conducted on the Nałęczów Plateau on loess soils showed similar organic carbon content in soils with different degrees of erosion, in the range of 1.36–1.24%, while in non-eroded soils it was 1.54% (Paluszek and Żembrowski, 2008). The relatively high biological activity of the studied soils—regardless of the degree of their erosional alteration—is confirmed by favorable organic-carbon-to-nitrogen ratios ranging between 9 and 11 (Tables 2 and 4). Soils with a C/N ratio of about 10 generally have good productive potential, as they supply plants with nitrogen in line with their needs while preserving a substantial pool of stable organic matter. In soils that are currently heavily and intensively eroded, the C/N ratio can fall well below 10 (Bauziene et al., 2008).

The high content of organic carbon is also reflected in the relatively high stocks of this element in the studied soils. Carbon stocks in surface layer up to 30 cm exceed 5 kg·m^{-2}, and in the case of eroded soils (P2, P4) even reach over 6 kg·m^{-2}, which is twice as high as in eroded humic clay-illuvial soils of the young-glacial areas of northern Poland (Świtoniak, 2023). In these areas, only some humic stagnic clay-illuvial soils exceeded values of 5 kg·m^{-2}. Significantly lower carbon stocks in the arable layer in these clay-illuvial soils (Retisols/Luvisols) of the young-glacial zone may result from the landform—a significant share of short but convex (subject to truncation) slope fragments due to numerous, though small, moraine hills. Another factor limiting the development of humus horizons in the north and central Poland is the less favorable climatic moisture index—annual precipitation is about 200 mm lower with similar average annual air temperatures. Meanwhile, Luvisols of the Wieliczka Foothills are formed from loess-like deposits with very good water-air properties, which, combined with favorable climatic conditions, leads to increased humus accumulation and the widespread periodical increase of moisture in these soils (Zasoński, 1989).

The effect of erosional redeposition of humus material in the studied soils is visible in the total carbon stocks considered across the entire soil profile thickness. In the clay-illuvial soils overlain by colluvium (Tab. 2, P3), these stocks exceeded 10 kg·m^{-2}, compared to about 6–8 kg·m^{-2} in the other Luvisols.

A certain influence of slope processes was also noted for the cation exchange capacity of the studied soils. With decreasing elevation along the slope, an increase in the sum of base cations, cation exchange capacity, and base saturation was observed. The lowest values of these parameters were recorded in the soil located in the upper part of the slope, while the highest values characterized the colluvial soil. The influence of slope processes, however, does not clearly differentiate the agricultural value of the studied soils. All analyzed profiles represent the bonitation class IIIa/IIIb and the 10th agricultural suitability complex—the so-called mountain wheat complex—which allows the cultivation of the same species as on the high agricultural value soils of the lowlands.

5. Conclusions

The conducted research allows drawing the following conclusions:

– Clay-illuvial soils (PSC, 2019) or Retisols/Luvisols (IUSS Working Group WRB, 2022) are the dominant component of the soil cover in the studied area. Soils that could be classified as brown soils (PSC, 2019) or Cambisols (IUSS Working Group WRB, 2022) were not identified;
– The morphological similarity of many of the studied clay-illuvial soils (Luvisols) to brown soils (Cambisols) results from erosional transformations of the soil cover, leading to the disappearance of eluvial horizons.
– The location of the studied soils in the transfer zone and on straight slopes, despite reaching inclinations of up to 10°, has limited the impact of slope processes on the spatial differentiation of the quality of surface humus horizons. Regardless of their position in various parts of the slopes, these horizons are relatively well developed, and only the criterion of light color prevents their classification as mollic/mollik horizons.

Due to the limited scope of the study, a deeper interpretation of the discussed issues requires further research over a larger area of the Wieliczka Foothills and a more detailed comparative analysis with results obtained by other authors.

Acknowledgments

Analyses were carried out at the Laboratory of Environmental Analyses (LEA), Faculty of Earth Sciences and Spatial Management, Nicolaus Copernicus University in Toruń. Acknowledgments for the initiative and organization of the scientific camp are extended to Mr. Daniel Pacek (Bemke Campus); Dr. Maciej Markiewicz and members of The Ludomir Sawicki Geographers' Circle of the Jagiellonian University for participating in the fieldwork.

Conflict of interest

The authors declare no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Julia Dziczek – Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Marcin Sykuła** – Methodology, Validation, Visualization, Writing – review & editing. **Marcin Świtoniak** – Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. All authors read and approved the final manuscript.

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Wpływ erozji na przestrzenną zmienność głównych właściwości, genezy i pozycji systematycznej gleb Pogórza Wielickiego na przykładzie obszaru Campusu Bemke

Słowa kluczowe

Gleby płowe
Gleby brunatne
Ogłowienie gleb
Morfologia stoków
Zasoby węgla organicznego

Streszczenie

Gleby płowe (główne odpowiedniki w klasyfikacji WRB: Luvisols i Retisols) stanowią podstawowy komponent pokrywy glebowej Polski. Procesy erozyjne, nasilone na terenach rolniczych o zróżnicowanej rzeźbie terenu, prowadzą do silnych przekształceń profili tych gleb. W wyniku erozyjnego spłycenia gleby te bardzo często morfologicznie upodobniają się do gleb brunatnych. Dotychczasowe opracowania z obszaru Pogórza Karpackiego wskazują na znaczny udział zarówno gleb płowych (w tym zerodowanych) jak i brunatnych. Rozróżnienie tych gleb nadal potrafi być jednak problematyczne. Celem pracy była ocena wpływu procesów erozyjnych na zmienność przestrzenną pokrywy glebowej w zachodniej części Pogórza Wielickiego, na przykładzie Campusu Bemke. W szczególności skupiono się na identyfikacji głównych typów gleb (rozróżnieniu gleb płowych zerodowanych i gleb brunatnych) oraz powiązaniu ich właściwości z morfometrią stoków i intensywnością przekształceń erozyjnych. Badania przeprowadzono w zachodniej części Pogórza Wielickiego, na terenie Campusu Bemke w Kleczy Dolnej. Obszar ten charakteryzuje się zróżnicowaną rzeźbą terenu, obecnością pokryw lessopodobnych i intensywnym użytkowaniem rolniczym. We wszystkich badanych glebach stwierdzono obecność poziomów iluwialnych (argik). W górnych, mniej nachylonych częściach stoków zachowały się poziomy wymywania, natomiast na stokach bardziej nachylonych poziomy Bt zalegają bezpośrednio pod poziomem próchnicznym. Ukształtowanie terenu (prostolinijne, transferowe stoki) ograniczało intensywność erozji, co skutkowało brakiem gleb całkowicie zerodowanych i zachowaniem stosunkowo dobrej jakości powierzchniowych poziomów próchnicznych, niezależnie od stopnia zerodowania i położenia na stoku. Zasoby węgla organicznego w warstwie powierzchniowej były wyższe niż w porównywalnych glebach młodoglacjalnych Polski północnej. Wyniki wskazują na potrzebę rozszerzenia badań o większy obszar i pogłębione analizy porównawcze.