SOIL SCIENCE ANNUAL
2023, 74(4), 176684

https://doi.org/10.37501/soilsa/176684

Assessment of soil organic carbon stocks differentiation in humus horizons of clay-illuvial soils within young morainic landscapes, northern Poland

Marcin Świtoniak*

Nicolaus Copernicus University in Toruń, Faculty of Earth Sciences and Spatial Management, ul. Gagarina 11, 87-100 Toruń, Poland

* dr hab. M. Świtoniak, swit@umk.pl, ORCID iD: https://orcid.org/0000-0002-9907-7088

Received: 2023-08-12
Accepted: 2023-12-09

Associated editor: E. Błońska

Keywords:

Luvisols
Erosion
Humus horizons
Soil classification
Stagnic properties
Soil truncation

Abstract

Clay-illuvial soils (Luvisols or Retisols in WRB) are the most widespread component of soil cover in Poland. Due to common occurrence and relatively high fertility they are crucial for food production. Agricultural use of these soils, however, leads to strong alterations and, in many cases, their degradation. This is especially important in young morainic landscapes of northern Poland. Hummocky and undulating relief combined with agricultural use, leads to truncation of clay-illuvial soils and generally affect the quality of humus horizons and soil organic carbon (SOC) content. The aim of the presented study is to assess the overall SOC stocks in plough horizons of clay-illuviated soils and their differentiation between their most common subtypes (according to Polish Soil Classification 2019). SOC stocks were calculated for 72 soil profiles. The average stocks were low – 3.28 kg·m^{-2} which may be related to both: natural conditions and strong anthropogenic alterations. Based on the obtained results separate subtype attributes, although express the variability of clay-illuvial soils, do not reflect the diversity of humus pools. However, it can be stated that SOC stocks differ statistically in particular complex subtypes. The highest SOC stocks (4.12 kg·m^{-2}) were recorded in the humic stagnogleyic clay-illuvial soils (Stagnic Luvisols/Retisols in WRB) characterized by relatively high soil moisture and a low erosive transformations. Truncated pedons (Ap-Bt-C(k)) were divided into two common subtypes – eroded humic clay-illuvial soils and eroded clay-illuvial soils (Haplic Luvisols). Eroded humic subtype had quite high average SOC stocks – 3.61 kg·m^{-2}, the second subtype had extremely low carbon pools – 1.40 kg·m^{-2}. Such high diversity may result from different pace of erosion in particular profiles and regenerative, sustainable management (e.g. reduced ploughing, vineyards, grassland) leading to the rebuilding of SOC stocks in many of studied eroded humic pedons. Low stocks (2.24 kg·m^{-2}) were also noticed in typical clay-illuvial soils which humus horizons were also degraded by erosion. A slight erosional alterations characterized subtype of texturally contrasted humic clay-illuvial soils (Abruptic Luvisols / Haplic Planosols) with average stocks – 3.57 kg·m^{-2}. For further research larger database is necessary. Carbon stocks in the deeper horizons should also be investigated.

1. Introduction

Soils with significant leaching of the clay fraction and presence of diagnostic illuvial Bt horizon account more than 50% of Poland (Bednarek and Prusinkiewicz, 1997; Sykuła et al., 2019). According to newest, 6th edition of Polish Soil Classification (PSC, 2019) such soils, where Bt horizons are the main diagnostic component (which means lack of organic, anthropogenic or humus diagnostic horizons for example), are classified as a clay-illuviated soil type (PSC, 2019; Kabała et al., 2019) which corresponds mainly to Luvisols, Retisols or Planosols in World Reference Base for Soil Resources (IUSS Working Group WRB, 2022). These soils in scale of whole country are mostly derived from loamy glacial tills or silty loess deposits and have average high fertility/productivity. Due to their common occurrence and great importance in agriculture, clay-illuviated soils have been the subject of many multithreaded studies focused on clay illuviation process or their general genesis and characteristics (e.g. Konecka-Betley et al., 1970, Uggla and Ferczyńska, 1975; Zasoński, 1981; Chojnicki, 1993; Świtoniak, 2008, 2021; Szymański and Skiba, 2013; Musztyfaga and Kabała, 2015; Waroszewski et al., 2021; Gus-Stolarczyk et al., 2023), micromorphological features (e.g. Zasoński, 1974, 1979, 1983; Mroczek, 2018), anthropogenic transformations (Marcinek and Komisarek, 2004; Radziuk and Świtoniak, 2021, 2022; Loba et al., 2021, 2023), quality assessment (Świtoniak, 2007; Kobierski et al., 2015) or other aspects.

Some of the studies were an attempt to determine the quality and quantity of organic matter in clay-illuvial soils (e.g. Sytek, 1972; Kuźnicki and Skłodowski, 1979; Kalembasa and Kalembasa, 2011; Sosulski et al. 2013).

Despite the vast amount of studies focused on clay-illuvial soils, few research tried to evaluate SOC stocks in these type of pedons within young morainic landscapes of Poland. Marcinek and Komisarek (1993) estimated soil organic matter content and its spatial variability in clay-illuvial soils of Wielkopolska, whereas Kobierski and Wojtasik (2009) and Wiśniewski and Märker (2021) identified coal pools in several profiles of similar soils of other South-Baltic Lakelands. Moreover, carbon stocks were measured in Luvisols of Kujawy region (Kobierski et al. 2015). The influence of erosion on the soil carbon stocks in clay-illuvial soils of the Vistula Valley slopes was the main aim of research conducted by Świtoniak et al. (2015). However, most of mentioned authors point to a tangible spatial differentiation of the properties of humus horizons and SOC stocks resulted from the natural, vast heterogeneity of clay-illuviated soils and imposing on it impact of human-induced erosion. Research conducted on various forest habitats in central Poland by Zwydak et al. (2017) showed that overgrown by broadleaf forests Luvisols had significantly lower carbon resources, compared even to the less fertile Arenosols and Podzols covered by Scots pine stands which led the formation of ectohumus and higher C accumulation in surface horizons. Apart from those research, the variability of carbon pools was more often determined for mountainous, forested or reclaimed areas where clay-illuvial soils do not represent a significant share (Józefowska and Miechówka, 2011; Świtoniak et al., 2011; Szopka et al., 2016; Greinert et al., 2018; Łabęda and Kondras, 2020; Porębska et al., 2021; Sewerniak et al. 2023). The results of the all above mentioned studies shows that clay-illuviated soils of Poland are generally characterized by lower storage capacity of humus in comparison with most of other types. It was also confirmed in many other regions of the word. Luvisols showed the lowest SOC stocks in the top 100 cm (6.45 kg m^{-2}) among main Reference Soil Groups occurred in Brasil – even lower than highly weathered tropical soils as Plinthosols Ferralsols or Acrisols (Gomes et al., 2019). Jarmain et al. (2023) also confirm that Luvisols have one of the lowest carbon retention capacities compared with other soils. In other hand – global average stocks of SOC about 4.5 kg m^{-2} calculated for Luvisols (FAO and ITPS, 2020) is significantly lower than in humus-rich pedons (Gleysols, Chernozems, Phaeozems), similar to humid tropical soils (Ferralsols, Acrisols, Lixsisols, Plinthosols) but higher than in most reference groups typical for semi-arid and arid regions (Arenosols, Calcisols, Gypsisols, Solonchaks). Despite the wealth of global data on SOC stocks, existing databases are not free from shortcomings. Due to the lack of high-resolution, detailed regional data and deficiencies in the laboratory data (e.g. bulk density and skeleton content), many models or calculations are simplified, which leads to incorrect results – often overestimation of SOC stocks (Poeplau et al., 2017). Significant deviations of the model results from the actual values may also occur in areas with intensive relief, where significant changes in the properties of humus horizons over short distances occur. For this reason frequent attempts are made to develop models based on high-resolution local field and laboratory data and machine learning (Hateffard et al., 2022, 2023) which enable obtaining increasingly reliable results. This is very important not only from a production (farming, forestry) point of view, but also for understanding the natural carbon cycle processes and counteracting climate change (e.g. Batjes, 1998; Lal, 2004; Scharlemann, et al. 2014).

Taking the above into account, further research on soil carbon pools in clay-illuviated soils within young morainic areas seems to be necessary. The main objective of the work is to determine the overall soil organic carbon stocks in surface horizons of clay-illuvial soils of northern Poland. Particular emphasis was placed on comparison of the obtained data with the results of other studies and estimation of the differences of SOC stocks between the most common subtypes (PSC, 2019) of clay-illuviated soils within investigated area.

2. Study area and methods

The study was carried out in young morainic area covered by the maximum extent (Marks, 2012) of the last glaciation (Vistulian) in northern Poland. The main outline of the relief of the discussed area was being formed in the Pomeranian (16–17 kyr BP) and Gardno phase (15–16 kyr BP).

The area is located in the zone of moist and cool temperate climate (IPCC, 2006). According to Köppen−Geiger Climate Classification, the region is located in the fully humid zone with temperate and warm summer (Kottek et al., 2006). Average annual air temperatures calculated for period 1991–2020 were from about 8°C in eastern to 9°C in south-western part of investigated region. The average annual precipitation is about 550–650 mm with the majority of precipitation occurring in summer (Tomczyk and Bednorz, 2022). Due to the predominance of rainfall over potential evaporation, most soils are characterized by the leaching type of soil water regime.

72 profiles were studied to the depth of 150 cm. Most of the profiles were located in morainic plateaus within thirteen physico-geographical mesoregions represent 6 macroregions (Fig. 1; Kondracki, 2009; Solon et al., 2018): South Pomeranian Lake District (11 profiles), Iława Lake District (3 profiles). Chełmno-Dobrzyń Lake District (49 profiles), Wielkopolska Lake District (5 profiles), Staropruska Plain (1 profile) and Mazurian Lake District (3 profiles). Investigated morainic plateaus were built with Pleistocene glacial tills in some cases covered (1–2 m thick) by fluvial, fluvioglacial or ablation sandy/loamy materials (Niewiarowski, 1959; Niewiarowski and Wysota, 1986; Świtoniak 2006, 2014; Karasiewicz et al., 2019; Woronko et al. 2022). All of studied soils were used as arable lands recently. In some cases the way of use has been changed during last few years to reduced tillage (strip-till – 5 profiles), grasslands (5 profiles) or vineyards (4 profiles). Most studied soils are still under intensive agricultural management (ploughing).

All profiles were described in stage of field works. 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). Bulk soil samples were collected

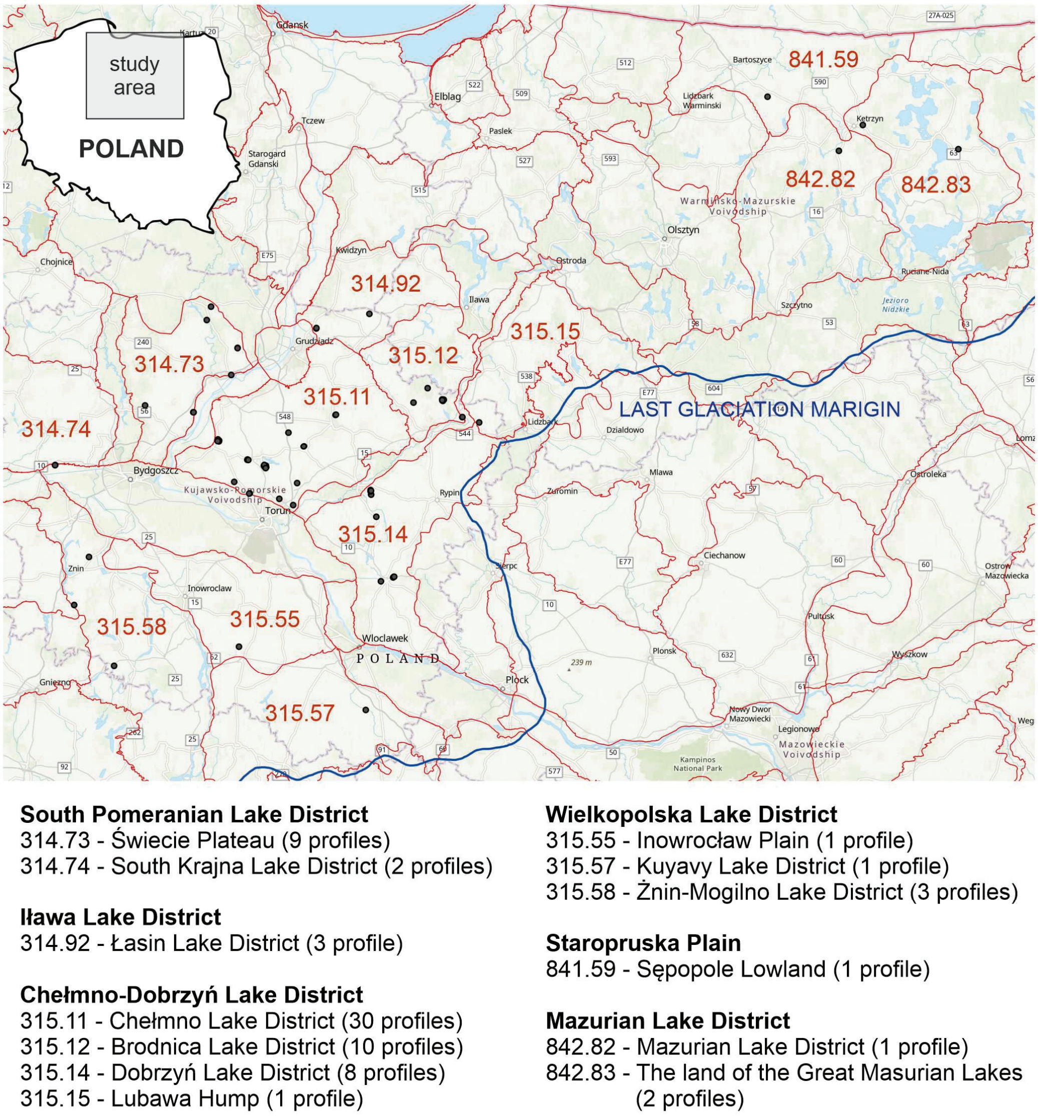


Fig. 1. Localization of studied soils within physico-geographical mesoregions of Poland

from every distinguished soil horizons. Standard soil analyses were performed using the methods as follows: soil organic carbon (SOC) content – by wet oxidation Tyurin's method; total nitrogen content by Kjeldahl method; $CaCO_3$ content – volumetric Scheibler method; particle-size distribution – by sieve and sedimentary areometric method; pH of soil-to-solution ratio of 1:2.5 using 1 M KCl and distilled H_2O as the suspension medium. Color has been described according to Munsell Soil Color Charts (2000).

Soil organic carbon stock SOCs ($kg \cdot m^{-2}$) were calculated using Eq. (1) up to the lower boundary of the humus horizon – in most cases it corresponded to the plough horizon only:

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

where: SOC – soil organic carbon content ($g \cdot kg^{-1}$); BD – bulk density ($g \cdot cm^{-3}$); t – thickness of horizon (m) and SK – content of gravel $\phi > 2.0$ mm.

The systematic position and symbols/names of diagnostic horizons were given after the sixth edition of the Polish Soil Classification (PSC, 2019) and WRB (IUSS, 2022). English-language names of soil units (PSC, 2019) were given as proposed by Kabała et al. (2019).

3. Results

Two main "patterns" of genetic horizons sequences were found in the studied clay-illuvial soils. In 38 cases soils had a clearly visible eluvial zone (mainly Ap-Et horizons) on clay-enriched argik (WRB: argic) Bt horizon and parent materials with secondary forms of calcium carbonate in bottom part of profile (whole sequence: Ap-Et-Bt-C(k)). The remaining 34 soils had Bt horizons directly below the plough layer (Ap-Bt-C(k)). Although the humus horizons did not meet the criteria of diagnostic epipedons (e.g. Mollik, Umbrik) their properties differed significantly

Table 1
Selected properties of humus horizons

	Thickness [cm]	BD [g·cm⁻³]	Clay [%]	Skeleton fraction [%]	SOC [g·kg⁻¹]	SOC stocks [kg·m⁻²]
Mean	**31.5**	**1.46**	**9.29**	**2.71**	**07.4**	**3.28**
SD	*7.0*	*0.10*	*6.18*	*4.01*	*02.1*	*1.18*
Max	50.0	1.74	31	35	14.3	5.97
Min	15.0	1.26	2	0,1	03.5	0.77

within the group of tested clay-illuviated soils (WRB: Luvisols, Retisols or Planosols). The thickness of humus horizons ranged from 15 to 50 centimeters (Tab. 1) – with a predominance of situations where they had 20–40 cm (Fig. 2a). These values are generally related to the depth of ploughing, which is confirmed by high homogeneity, a sharp lower limit of humus horizons and the history of land use. Bulk density varied between 1,26 and 1,74 with mean 1,46 [g·cm^{-3}] (Tab. 1). These values were normal as for arable soils developed from young morainic materials (e.g. Suuster et al. 2011) and in most cases (Fig. 2b) indicates no restriction for roots growth (USDA Natural Resources Conservation Service, 2008).

The grain size distribution of the humic horizons had low amount of skeleton fraction (Tab. 1, Fig. 2c) and represented a wide range of textural classes – from sand (4 horizons) and loamy sand (31) to sandy loam (8), loam (25) or sandy clay loam (4) with maximum 31% of clay fraction content. There was a relatively large variation in the SOC content. In most humus horizons, it did not fall below 0.4% and did not exceed 0.9% (9 g kg^{-1}), but in some cases it reached over 1.2%. The calculated average carbon stocks was slightly more than 3 kg m^{-2} in the entire population of the studied soils, with almost seven-fold differences between the minimum (0.77 kg m^{-2}) and maximum (5.97 kg m^{-2}) values According to the rules of the latest version of the Polish

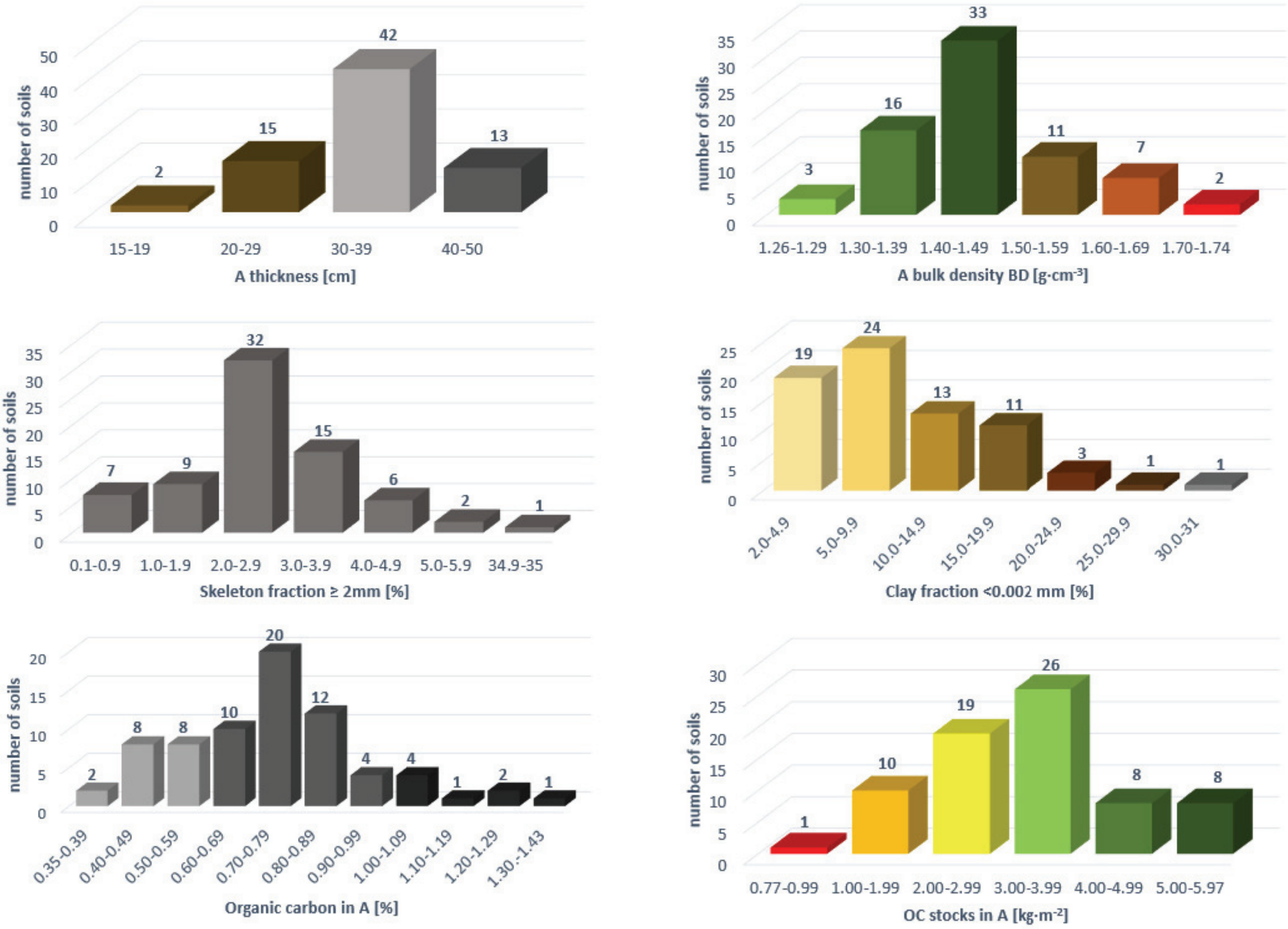


Fig. 2. Selected characteristics of investigated humus horizons and organic carbon stocks

Soil Classification (PSC, 2019) within clay-illuviated soils thirteen subtypes (further called "subtype attributes") were defined on the priority list: eroded, texturally contrasted, lamellic, humic, brown, rusty, podzolic, vertic, waterlogged, gleyic, stagnogleyic, tonguing, typical (Kabała et al. 2019). Seven subtype attributes were identified in the studied population of soils: eroded – 34 cases; texturally contrasted – 12; lamellic – 1; humic – 55; rusty – 3; stagnogleyic – 28; tonguing – 8. Moreover 4 profiles represent the simplest characteristic for the type expression of soil features and were classified as typical clay-illuviated soils (tab. 1). Brown, podzolic, vertic, waterlogged, gleyic subtype attributes were not detected. In seventeen profiles only 1 subtype attribute matched the soil properties, in 39 – two, 14 – three, and in 2 studied soils sets of their features matched the description of four subtype attributes. According to the PSC, maximum two subtype attributes (the first on the priority list) can be considered when constructing the full name of a soil subtype (further called just "subtype" or "complex subtype"). In pedons with features fit for more than 2 subtype attribute – those that are further on the list are taken into account in the name of the lower rank taxon as soil variety – in parentheses after the name of the subtype (Table 1).

The mean values of SOC stocks in soil groups divided into all subtype attribute (regardless of whether they were included in the name of the subtype or variety of the tested soil), ranged from 2.25 kg·m^{-2} for typical to 3.66 kg·m^{-2} in humic attribute group.

Thirteen subtypes of studied clay-illuviated soils were distinguished – mostly in the form of complex subtypes (with two subtype attributes). The most numerous were: eroded humic (26 profiles), humic stagnogleyic (13) texturally contrasted humic (10), eroded (6) and typical (4). Soil organic carbon stocks varied significantly in individual subtypes – from 1.4 in eroded to 4.11 kg·m^{-2} in humic stagnogleyic clay illuvial soils (Fig. 4). Examples of the morphology and basic properties of these subtypes were presented in Table 3 and in the Fig. 5.

Table 2
Classification of studied clay-illuvial soils

Quantity of profiles	Subtype attribute									Subtype/complex subtype (PSC 2019)	Variety (PSC 2019)	WRB (2022)
	Eroded	Texturally contrasted	Lamellic	Humic	Brown	Rusty	Stagnogleyic	Tonguing	Typical			
6	x									Eroded	–	Haplic Luvisol
21	x			x						Eroded humic	–	Haplic Luvisol
5	x			x			o				(stagnogleyic)	
2	x						x			Eroded stagnogleyic	–	Stagnic Luvisol
1		x								Texturally contrasted	–	Abruptic Luvisol
4		x		x						Texturally contrasted humic	–	Abruptic Luvisol / Haplic Planosol
1		x		x		o					(rusty)	
1		x		x		o	o				(rusty, stagnogleyic)	
3		x		x			o				(stagnogleyic)	
1		x		x			o	o			(stagnogleyic, tonguing)	
1		x				x				Texturally contrasted rusty	–	Abruptic Luvisol
1			x	x			o			Lamellic humic	stagnogleyic)	Lamellic Luvisol
3				x						Humic	–	Haplic Luvisol
9				x			x			Humic stagnogleyic	–	Stagnic Luvisol / Stagnic Retisol
4				x			x	o			(tonguing)	
2				x				x		Humic tonguing	–	Haplic Retisol
2							x			Stagnogleyic	–	Stagnic Luvisol
1								x		Tonguing	–	Retisol
4									x	Typical	–	Haplic Luvisol

Identified subtype attributes in studied soils: x – taken into account in the full name of the subtype
o – not taken into account in the full name of the subtype

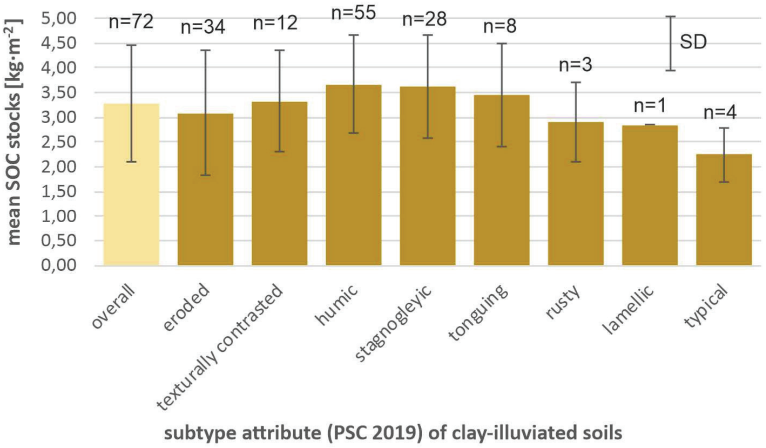


Fig. 3. Mean organic carbon stocks in groups of soils divided by occurring subtype attributes

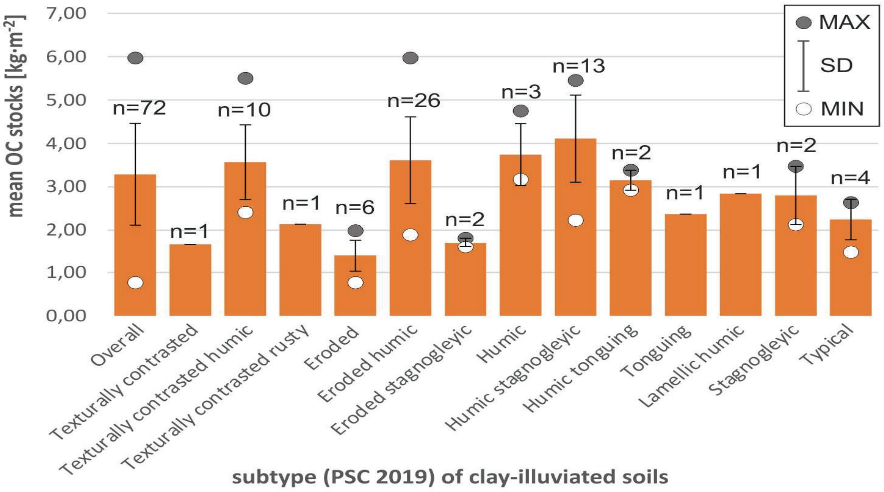
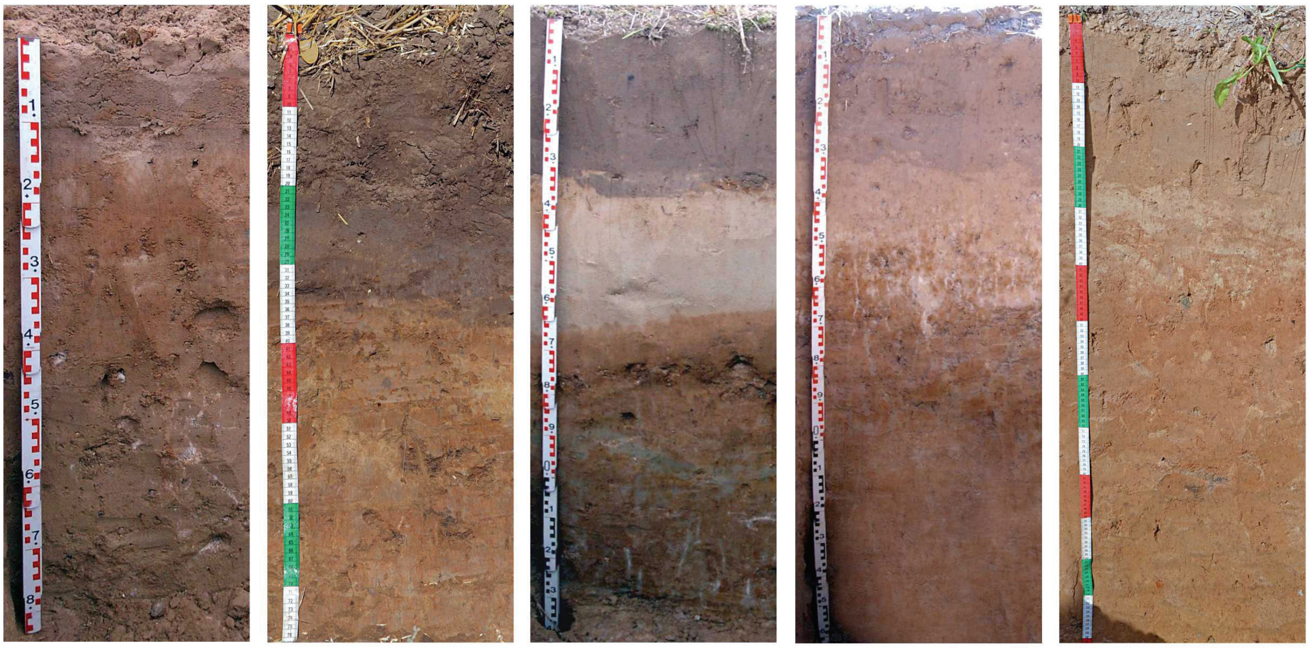


Fig. 4. Mean organic carbon stocks in subtypes of studied clay-illuviated soils



Eroded

Eroded humic

Texturally contrasted humic

Humic stagnogleyic (tonguing)

Typical

Fig. 5. Morphology of exemplary soils for the most common subtypes

Table 3
Basic properties and TOC stocks of exemplary soils for the most common subtypes

Horizon	Depth [cm]	Skeleton fraction	Particle size distribution [%]			Texture	BD [$g \cdot cm^{-3}$]	SOC [$g \cdot kg^{-1}$]	TN [$g \cdot kg^{-1}$]	C:N	pH		$CaCO_3$ [$g \cdot kg^{-1}$]	SOC stocks [$kg \cdot m^{-2}$]
			2.0–0.05	0.05–0.002	< 0.002						H_2O	KCl		
P1 – Eroded clay-illuvial soil ***Haplic Luvisol (Epiloamic, Katoarenic, Aric, Protocalcic, Ochric)***														
Ap	0–15	2	73	16	11	SL	1.49	3.5	0.38	9	6.1	4.7	–	0.77
Bt	15–45	2	70	16	14	SL	1.74	–	–	–	6.8	5.0	trace	–
Ck	45–(90)	11	78	15	7	LS	1.65	–	–	–	8.7	8.0	61	–
P29 – Eroded humic clay-illuvial soil ***Haplic Luvisol (Pantoloamic, Aric, Protocalcic, Ochric)***														
Ap	0–32	2	63	26	11	SL	1.32	11.3	1.22	9	7.0	6.3	2	4.68
Bt	32–130	0	61	22	17	SL	1.65	–	–	–	7.0	5.7	2	
2Ck	130–(150)	2	33	43	24	L	1.59	–	–	–	8.1	7.4	140	
P37 – Texturally contrasted humic clay-illuvial soil ***Albic Abruptic Luvisol (Anoarenic, Endoloamic, Aric, Ochric, Raptic, Bathystagnic)***														
Ap	0–35	2	80	18	2	LS	1.47	5.4	0.59	9	6.0	5.2	–	2.72
Et	35–60/65	0	88	7	5	S	1.52	–	–		6.9	6.2	–	
2Bt	60/65–75	1	81	8	11	SL	1.59	–	–		7.4	6.2	1	
3Bt	75–95	1	64	25	11	SL	1.71	–	–		7.7	6.9	2	
3Ckg	95–(140)	2	41	28	11	L	1.70	–	–		8.4	7.5	72	
P57 – Humic stagnogleyic clay-illuvial soil (tonguing) ***Eutric Albic Stagnic Retisol (Pantoloamic, Aric, Ochric)***														
Ap	0–35	2	68	27	5	SL	1.51	8.0	0.8	10	5.0	3.9	–	4.15
Et	35–50	1	68	23	9	SL	1.65	–	–	–	5.5	4.3	–	
E/Bg	50–70	1	59	22	19	SL	1.51	–	–	–	5.7	4.3	–	
Btg	70–120	1	46	23	31	SCL	1.73	–	–	–	5.3	3.8	–	
Ck	120–(160)	2	44	29	27	CL	1.77	–	–	–	8.2	7.2	77	
P 69 – Typical clay-illuvial soil **WRB 2022 –** ***Albic Abruptic Luvisol (Epiarenic, Katoloamic, Cutanic, Epidystric, Ochric)***														
A	0–10	3	77	18	5	LFS	1.38	4.7	0.45	10	5.3	4.5	–	0.64
A(p)	10–27	2	77	17	6	LFS	1.55	3.2	0.34	9	4.8	3.9	–	0.83
Et	27–40	2	76	19	5	LFS	1.59	–	–	–	5.2	4.3	–	–
Bt	40–100	2	65	18	17	SL	1.75	–	–	–	6.8	5.3	–	–
BC	100–170	2	70	17	13	SL	1.65	–	–	–	7.2	6.0	trace	–
Ck	170–(200)	3	65	22	13	SL	1.61	–	–	–	8.4	7.7	51	–

4. Discussion

4.1. Average SOC stock

Average (mean) SOC stocks in the humus horizons (with average thickness 31.5 cm) of studied group of soils were relatively low. A value 3.28 kg m^{-2} is more than 2 times lower than the average SOM stocks (8.16 kg m^{-2}) calculated globally for the upper 30 cm layer within all available (without sandy soils and soils with a very high content of humus) cropland soils (Zomer et al. 2017). Compared to the average stocks of SOM in European arable soils (10.6 kg· m^{-2}), it is even three times less (Zomer et al. 2017). Significantly higher values calculated to the depth of 30 cm were also obtained in many regional studies of similar clay-illuviated soils (Luvisols) in other mid-latitude countries e.g.: 5.91 $kg \cdot m^{-2}$ in freshly afforested previously arable Luvisols of Central and Southern Lithuania (Varnagirytė-Kabašinskienė et al. 2021) or 6.7 $kg \cdot m^{-2}$ in croplands of Lithuania (Armolaitis et al., 2022); 6.23 $kg \cdot m^{-2}$ for Luvisols in Denmark (Adhikari et al. 2014), 9–11.2 $kg \cdot m^{-2}$ in group of arable "slightly stagnogleyic Luvisols" near Essen – Germany (Burghardt et al. 2018) or even 11.1 $kg \cdot m^{-2}$ in Ireland (Jarmain et al. 2023).

The obtained mean values of SOC stocks are definitely more similar to the results obtained for Luvisols in regions characterized by a warmer climate, not favorable to the accumulation of significant carbon resources in humus horizons. Comparable carbon stocks have been found in the surface humus horizons (0–20 cm) of arable Luvisols of Southern Ethiopia – 3.45 kg·m^{-2} (Yitbarek, 2019), in uppermost layer (30 cm) in Luvisols of Andalusia – 2.87 kg·m^{-2} (Muńoz-Rojas et al., 2012) or in upper 30 cm in Luvisols under conventional farming systems in the semi-arid region of Brazil – 3.69 kg·m^{-2} (Maia et al. 2007).

Newest global-scale models based on broad soil databases also indicates the relatively low carbon sequestration in majority of soils within the young glacial areas of northern Poland. For example, estimated average SOC stocks in the 0–30 cm layer calculated by Global Soil Organic Carbon Map v 1.5 (FAO and ITPS, 2020) for the vicinity of the tested soils (in grids of about 0.5 km^2 for each tested soil) amounted only 4.96 kg·m^{-2}. Map of SOC stocks created within project SoilGrids shows values for most of investigated area between 3.5–4.5 kg·m^{-2} (Poggio, et al. 2021). Similar, low stocks of organic carbon were also confirmed by regional studies of other authors in Poland. According to Markiewicz et al. (2014) agricultural clay-illuvial soils (Luvisols) are one of the most humus-poor soil types (together with sandy rusty soils and arenosols) of Brodnica Landscape Park and have about 5.5 kg·m^{-2}. Overall, low humus stocks in autogenous soils (like most of Luvisols supplied only by rainwater) in the region may be caused by climatic conditions. Central part of Poland is characterized by low values of Standardized Precipitation-Evapotranspiration Index which indicates periodic water shortages in the soils (Pińskwar et al., 2020). In addition, the soils of the region are degrading as a result of anthropogenic drainage and suffer from increasingly frequent droughts (Jadczyszyn and Bartoszewicz, 2020). Moderate or even low soil moisture can accelerate the mineralization of organic matter and reduce the SOM stocks of humus horizons – especially in soils intensively used for agriculture. Although soil moisture is a factor that most strongly influences the carbon accumulation (Błońska and Lasota, 2017), the detailed impact of it on SOC stocks has not been fully explored (Kerr and Ochsner, 2020).

Low organic carbon stocks in the studied clay-illuvial soils may also be caused by insufficient fertilization – especially organic. This is also important in the case of poor balance with mineral fertilizers, the excess of which may lead to an even faster loss of organic carbon resources in plough horizons (Jaskulska and Jaskulski, 2003).

Another important issue in the context of the discussed low SOC stocks is human-induced erosional processes which lead to the degradation of soils and depletion in SOC content and shallowing of humus horizons (Sinkiewicz, 1998; Podlasiński, 2013; Świtoniak et al. 2016; Radziuk and Świtoniak, 2022; Sowiński et al. 2023). The influence of slope processes on the properties of the studied soils is evidenced by their morphology – nearly half of them (34 profiles) had Bt horizons directly below plough horizons – which is the effect of erosive truncation. Similar erosive transformations and low carbon stocks in the clay-illuviated soils within young morainic landscapes of Poland were also recorded by other authors. For example Wiśniewski and Märker (2021) in studies of eroded agricultural moraine slopes measured SOC stocks in Ap horizons of Luvisols below 3 kg·m^{-2}. In Krajna Lake District and Chełmno Lakeland eroded Luvisols had SOC stocks in Ap horizons 3.87–5.39 kg·m^{-2} and 3.80–4.47 kg·m^{-2} respectively (Kobierski and Wojtasik, 2009). Moreover Kobierski et al. (2015) obtained values 3.80 to 4.81 kg·m^{-2} in Luvisols of Kujavy.

4.2. Variability of SOC stocks in accordance with subtype attributes

Regardless of the low overall values – the studied group of soils is characterized by significant variability of soil organic carbon stocks. In 11 profiles these stocks were below 2 kg·m^{-2}, while in 16 profiles they exceeded 4 kg·m^{-2}. The reason for such high differences may be both the primary diversity of the described clay-illuviated soils (like texture, moisture conditions) and significant anthropogenic transformations (e.g. degradation resulting from intensive agricultural use, human-induced erosion). The heterogeneity of the profiles is reflected in the wide range of attributes used to define the subtypes of studied clay-illuviated soils. In individual groups of soils distinguished on the basis of these attributes, some differentiation of SOC mean values was

Table 4
An absolute difference between the means of SOC stock calculated for particular subtype attribute

Subtype attribute	eroded	texturally contrasted	humic	stagno-gleyic	tonguing	rusty	typical
eroded	0	0.24	0.58	0.55	0.38	0.19	0.84
texturally contrasted	0.24	0	0.34	0.31	0.14	0.43	1.08
humic	0.58	0.34	0	0.034	0.2	0.77	1.42
stagnogleyic	0.55	0.31	0.034	0	0.17	0.74	1.39
tonguing	0.38	0.14	0.2	0.17	0	0.57	1.22
rusty	0.19	0.43	0.77	0.74	0.57	0	0.65
typical	0.84	1.08	1.42	1.39	1.22	0.65	0

1.75 – an absolute difference between the means of the pairs which are statistically homogeneous according to Tukey's post-hoc test, $p<0.05$
2.17 – an absolute difference between the means of the pairs which are significantly different according to Tukey's post-hoc test, $p<0.05$

noted (Fig. 3). Due to the high variability within particular "attribute groups", they are not statistically significant (Table 4).

The highest mean value (3.66 kg·m^{-2}) was recorded in soils (55 profiles) with attribute humic. It results from a significant thickness (over 30 cm) or high quality (meets all mollik/umbrik (PSC, 2019) criteria but is less than 30 cm) of the humus horizon. In this group 6 profiles had relatively high SOC stocks above 5 kg·m^{-2} but in 14 profiles the SOC stocks did not reach 3 kg·m^{-2}. Moreover, 11 profiles had a small SOC content – below 0.6%, This is due to the fact that many soils with poorly developed Ap horizons meet the criteria of the humic attribute due to the depth of agricultural practices – ploughing usually reaches up to 30 cm. In addition, in 26 cases of this group, significant erosional shallowing of the soil profiles (A-B-C sequence of horizons) was note. Therefore, the humic attribute does not specify the general state of development of the surface horizon and, as was noted in previous studies (Świtoniak 2021, Świtoniak et al. 2022), its criteria should be revised. A good solution seems to be to raise the carbon content to a minimum of 0.6%. Such a change would increase the average value of SOC stocks to statistically significant 3.96 kg·m^{-2}.

High mean values – 3.63 kg·m^{-2} were obtained for the group (28 cases) of profiles with stagnogleyic attribute. In these soils, it may be related to periodically higher moisture of the surface horizons (Błońska and Lasota, 2017). Stagnic properties appeared at a small depth – often directly below the plough horizons. This group is more homogeneous than the previous one – only in 2 cases SOC content was lower than 0.6% and in 6 profiles erosional shallowing was noted.

The last frequently used in studied soils (34 pedons) is the eroded subtype attribute. It would seem that these soils will have very homogeneous properties of humus horizons – associated with erosive shallowing and low carbon content. Meanwhile, although in 9 cases SOC stocks fall below 2 kg·m^{-2}, the mean value is not so low – 3.08 kg·m^{-2}. The attribute "eroded" is used on the basis of the current general morphology of the soil – the presence of the Bt horizon directly below the humus horizon. It does not take into account the current degree of development of Ap horizons, which can be very different in the studied soils – from heavily degraded to well-formed. In the group of discussed soils, nearly 30% is currently not ploughed – they are in reduced cultivation (strip-till), under vineyards or grasslands. Even a few years of such use can lead to the regeneration of the previously degraded humus horizon and a significant increase in SOC stocks. Organic carbon stocks in the mineral soils of grasslands in Poland in the 0–30 cm layer is quite high – 10.7 kg·m^{-2} which is the result of both – the high moisture of a significant part of these soils, but also due to the accumulation of humus by grass vegetation (Pietrzak and Hołaj-Krzak, 2022). The role of zero/reduced tillage or direct seeding in increasing carbon sequestration has been confirmed by many authors (Blecharczyk et al. 2007; Pikuła, 2019; Wang et al., 2020). For instance, reduced tillage compared with ploughing led to increasing cumulative (0–50 cm) SOC stocks on average 1.7% after 8–21 years of field experiment conducted in France, Germany, the Netherlands, and Switzerland (Krauss et al. 2022).

On the other hand Miechówka et al., (2012) found that carbon stocks are similar in arable fields and grasslands (mean values 9.09 and 8.99 kg·m^{-2} respectively) of Little and Silesian Beskids. According to their interpretation higher input of organic matter to the grassland soil was balanced by high doses of manure and mineral fertilizers in ploughing soils.

As can be seen from the above considerations, single subtype attributes were not sufficient to determine statistically significant differences in SOC stocks of studied clay-illuvial soils (Table 4). This is both due to the high diversity within individual "attribute groups" and to the fact that the particular profiles can have several attributes and the same soils may be taken into account for calculations in several groups – which is problematic in statistical research.

4.3. Variability of SOC stocks in accordance with (complex) subtypes

The situation is different in the case of full-named soil subtypes which are distinguishing on the base of complex soil features with the simultaneous separation of individual soils – assigning one soil to only one subtype (Kabała et al. 2019). The obtained results allow to conclude that some subtypes differ statistically in terms of average SOC stocks (Table 5).

In the studied population of soils 5 subtypes were represented by at least 4 soil profiles (Fig. 4) and they were selected for further interpretation.

Highest mean SOC stocks (4.11 kg·m^{-2}) were found in humic stagnogleyic clay-illuviated soils. This subtype includes soils with thick A horizons (≥ 30 cm) and the presence of stagnic properties with the simultaneous exclusion of eroded pedons (Fig. 5). Humus horizons development was stimulated by higher moisture and was not disturbed by intensive slope processes. Substantial SOM stocks (mean 6.01 kg·m^{-2}) in Stgnic Luvisols were also noticed by Jonczak (2013) in Sławno Plain. Moreover, Wiesmeier et al. (2014) stated that SOC stock in soils with stagnic properties are higher than in Luvisols.

One of the highest mean value of SOM stocks (3.61 kg·m^{-2}) was obtained for eroded humic clay-illuvial soils. In these pedons, despite significant shallowing of solum (Bt occurs directly under A), the humus horizons have a considerable thickness (≥ 30 cm) and often a high content of organic carbon. Many of these soils (9 out of 26) have strongly regenerated well-developed surface horizons (Fig. 5) with good aggregate structure, which results from their current use – reduced tillage, grassland, vineyards. It indicates that this stage of profile truncation alone does not reflect the degree of humus horizon degradation. This phenomenon has already been described above when discussing the eroded subtype attribute.

A slight erosional alterations characterizes subtype of texturally contrasted humic clay-illuvial soils. These soils have sandy topsoil (horizons A and E) underlain by loamy material (Bt and C(k)) at depth 50–100 cm which is usually associated with presence of lithological discontinuity (Świtoniak, 2006). Despite significantly different morphology and physical properties (Fig. 5), these soils have SOC stocks similar (3.57 kg·m^{-2}) to eroded humic subtype.

Definitely lower (although statistically this difference is not significant) mean value of SOC stocks (2.24 kg·m^{-2}) have typical clay-illuviated soils. This is probably connected with degrada-

Table 5
An absolute difference between the means of SOC stock calculated for particular subtypes/complex subtypes

Subtype/complex subtype	Texturally contrasted humic	Eroded	Eroded humic	Eroded stagno-gleyic	Humic	Humic stagno-gleyic	Humic tonguing	Stagno-gleyic	Typical
Texturally contrasted humic	0	**2.17**	0.042	1.86	0.17	0.54	0.42	0.77	1.32
Eroded	**2.17**	0	**2.21**	0.31	**2.34**	**2.71**	1.75	1.4	0.85
Eroded humic	0.042	**2.21**	0	1.91	0.13	0.5	0.46	0.81	1.37
Eroded stagnogleyic	1.86	0.31	1.91	0	2.04	**2.41**	1.44	1.09	0.54
Humic	0.17	**2.34**	0.13	2.04	0	0.37	0.59	0.94	1.5
Humic stagnogleyic	0.54	**2.71**	0.5	**2.41**	0.37	0	0.96	1.31	**1.87**
Humic tonguing	0.42	1.75	0.46	1.44	0.59	0.96	0	0.35	0.9
Stagnogleyic	0.77	1.4	0.81	1.09	0.94	1.31	0.35	0	0.55
Typical	1.32	0.85	1.37	0.54	1.5	**1.87**	0.9	0.55	0

2.17 – an absolute difference between the means of the pairs which are significantly different according to Tukey's post-hoc test, $p<0.05$
1.75 – an absolute difference between the means of the pairs which are statistically homogeneous according to Tukey's post-hoc test, $p<0.05$

tion of humus horizons due to human-induced erosion. They were located mostly on sloping positions and average thickness of Ap horizons in these soils was only 20 cm. Moreover they have a very thin eluvial horizon and a small depth to the upper boundary to Bt horizons (up to 50 cm). According to the studies on Luvisols' truncation – these soils were shallowed by erosional processes (Świtoniak, 2014).

Eroded clay-illuvial soils have the lowest SOC stocks among all subtypes (1.40 kg·m^{-2}) and represent the lowermost class of organic carbon pools (Burghardt et al., 2018). This value, as well as the morphology (small thickness, light colour – similar to Bt horizons) and physical features (coarse blocky structure) of humus horizons, confirm that they are heavily degraded (Radziuk and Świtoniak, 2022). Moreover, these soils were located in the upper, convex fragments of steep slopes – prone to soil erosion. Described subtype was the only one that differed statistically in terms of SOC stocks from most of the units described above. A comparison of this subtype with eroded humic clay-illuvial soils (with have the same degree of truncation – Ap-Bt-Ck sequence of horizons) indicates that eroded clay-illuvial soils have high carbon sequestration capacity which can be achieved by more sustainable management. This is also confirmed by studies of other authors in young morainic landscapes of northern Poland (Wiśniewski and Märker, 2021). Nevertheless, the data obtained from spatial models, shows relatively low ability of described soils to increase the SOC stocks which is estimated at approximately only 0.01 kg·m^{-2}·yr^{-2} (FAO and ITPS, 2020).

5. Conclusions

Presented studies allows to draw some preliminary conclusions regarding SOC stocks in surface horizons of clay-illuvial soils. In general, the studied soils are characterized by surprisingly low humus pools (3.28 kg·m^{-2}) in comparison with similar pedons in other mid-latitude regions. This is due to both – climatic conditions and strong anthropogenic alterations. Common erosion leads to the degradation of clay-illuvial soils which is revealed through depletion of SOC stocks. Despite generally low pools of humus, the tested soils differ significantly in terms of SOC stocks. Proposed in Polish Soil Classification (2019) system for creating full name of subtypes by using the two most important (according to the ranking list) attributes quite well reflects the diversity of SOM stocks in studied agricultural soils:

- highest mean values (4.11 kg·m^{-2}) had humic stagnogleyic subtype – which is associated with relatively high seasonal moisture and a low erosive transformations;
- low stocks (2.24 kg·m^{-2}) were noticed in typical clay-illuvial soils which humus horizons were also degraded by erosion;
- eroded (but not humic!) clay-illuvial soils with severely degraded humus horizons stand out by the lowest SOC stocks (1.40 kg·m^{-2});
- humic eroded soils prevailed among the truncated pedons. They had well-developed humus horizons and high SOC stocks (3.61 kg·m^{-2}), which can be associated with both slow erosion processes or/and the regenerative phase resulting from new methods of sustainable management;
- a slight erosional alterations characterized subtype of texturally contrasted humic clay-illuvial soils with average stocks – 3.57 kg·m^{-2}.

Individual, separate subtype attributes, although express the variability of clay-illuvial soils, do not reflect the diversity of humus pools. Tightening the criteria for the humic subtype attribute could partly solve this problem. The remaining attributes, however, concern individual soil characteristics and are not directly related to the development of humus horizons.

For further research on the discussed issue, it is necessary to create a much larger database. Carbon stocks in the deeper horizons (mainly in Bt) should also be investigated. It is also important to develop algorithms for determining the spatial ranges of individual subtypes using remote sensing tools. Clay-illuvial soils, as the basis for agricultural production, are highly exposed to further degradation, but they also hold great possibilities in the context of the potential sequestration of organic carbon.

References

Armolaitis, K., Varnagirytë-Kabađinskienë, I., Ţemaitis, P., Stakënas, V., Beniuđis, R., Kulbokas, G., Urbaitis, G., 2022. Evaluation of organic carbon stocks in mineral and organic soils in Lithuania. Soil Use Manage 38, 355–368. https://doi.org/10.1111/sum.12734

Adhikari, K., Hartemink, A.E., Minasny, B., Bou Kheir, R., Greve, M.B., Greve, M.H., 2014. Digital Mapping of Soil Organic Carbon Contents and Stocks in Denmark. PLoS ONE 9(8), e105519. https://doi:10.1371/journal.pone.0105519

Batjes, N.H., 1998. Mitigation of atmospheric CO2 concentrations by increased carbon sequestration in the soil. Biology and Fertility of Soils 27, 3, 230–235. https://doi.org/10.1007/s003740050425

Bednarek, R., Prusinkiewicz, Z., 1997. Geografia gleb. PWN, Warszawa. pp. 287. (in Polish)

Blecharczyk, A., Małecka, I., Sierpowski, J., 2007. Long-term effects of tillage systems on physico-chemical soil properties. Fragmenta Agronomica 1, 93, 7–13. (in Polish with English summary).

Błońska, E., Lasota, J., 2017. Soil Organic Matter Accumulation and Carbon Fractions along a Moisture Gradient of Forest Soils. Forests 8, 448. https://doi.org/10.3390/f8110448

Burghardt, W., Heintz, D., Hocke, N., 2018. Soil Fertility Characteristics and Organic Carbon Stock in Soils of Vegetable Gardens Compared with Surrounding Arable Land at the Center of the Urban and Industrial Area of Ruhr, Germany. Eurasian Soil Science 51, 1067–1079. https://doi.org/10.1134/S106422931809003X

Chojnicki, J., 1993. Lessives soils developed from superficial formations of the Błonie-Sochaczew Plain. Roczniki Gleboznawcze – Soil Science Annual 44(3/4), 135–151. (in Polish with English summary).

FAO and ITPS. 2020. Global Soil Organic Carbon Map V1.5: Technical report. Rome, FAO. https://doi.org/10.4060/ca7597en

Gomes, L.C., Faria, R.M., de Souza, E., Veloso, G.V., Schaefer, C.E.G., Fernandes Filho, E.I., 2019. Modelling and mapping soil organic carbon stocks in Brazil. Geoderma 340, 337–350. https://doi.org/10.1016/j.geoderma.2019.01.007

Greinert, A., Drab, M., Śliwińska, A., 2018. Storage capacity of organic carbon in the reclaimed post-mining Technosols. Environment Protection Engineering 44, 1, 117–127. https://doi.org/10.5277/epe180109

Gus-Stolarczyk, M., Drewnik, M., Michno, A., Szymański, W., 2023. The origin and transformation of soil lamellae in calcareous and non-calcareous loess soils in the Central European loess belt – A case study from southern Poland. Catena 232, 107399, https://doi.org/10.1016/j.catena.2023.107399

Hateffard, F., Balog, K., Tóth, T., Mészáros, J., Árvai, M., Kovács, Z.A., Szatmári, G., 2022. High-Resolution Mapping and Assessment of Salt-Affectedness on Arable Lands by the Combination of Ensemble Learning and Multivariate Geostatistics. Agronomy 12, 8, 1858. https://doi.org/10.3390/agronomy12081858

Hateffard, F., Szatmári, G., Novák, T.J., 2023. Applicability of machine learning models for predicting soil organic carbon content and bulk density under different soil conditions. Soil Science Annual 74(1), 165879. https://doi.org/10.37501/soilsa/165879

Intergovernmental Panel on Climate Change (IPCC), 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Egglestone, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.). Intergovernmental Panel on Climate Change (IPCC), IPCC/IGES, Hayama, Japan.

IUSS Working Group WRB. 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

Jadczyszyn, J., Bartosiewicz, B., 2020. Procesy osuszania i degradacji gleb. Studia i Raporty IUNG-PIB 64(18), 49–60. https://doi.org/10.26114/sir.iung.2020.64.03

Jarmain, C., Cummins, T., Jovani-Sancho, A.J., Nairn, T., Premrov, A., Reidy, B., Renou-Wilson, F., Tobin, B., Walz, K., Wilson, D., Byrne, K.A., 2023. Soil organic carbon stocks by soil group for afforested soils in Ireland. Geoderma Regional 32, e00615. https://doi.org/10.1016/j.geodrs.2023.e00615

Jaskulska, J., Jaskulski, D., 2003. Influence of many years' fertilization on the dynamics of soil properties. Postępy Nauk Rolniczych 4. 21–35. (in Polish with English summary).

Jonczak, J., 2013. Soil organic matter properties in Stagnic Luvisols under different land use types. Acta Agrophysica 20(4), 565–575.

Józefowska, A., Miechówka, A., 2011. Comparison of the results of determining the organic carbon in soils of the Carpathian Foothills obtained by the Tiurin and dry combustion method (thermal method). Roczniki Gleboznawcze – Soil Science Annual 62(1), 65–69. (in Polish with English summary)

Kabała, C., Charzyński, P., Chodorowski, J., Drewnik, M., Glina, B., Greinert, A., Hulisz, P., Jankowski, M., Jonczak, J., Łabaz, B., Łachacz, A., Marzec, M., Mendyk, Ł., Musiał, P., Musielok, Ł., Smreczak, B., Sowiński, P., Świtoniak, M., Uzarowicz, Ł., Waroszewski, J., 2019. Polish Soil Classification, 6th edition – principles, classification scheme and correlations. Soil Science Annual 70(2), 71–97. https://doi.org/10.2478/ssa2019-0009

Kalembasa, D., Kalembasa, D., 2011. Fractions of nitrogen and carbon in humus horizons of arable luvisols and cambisols located on Siedlce Upland. Acta Agrophysica 18, 1, 7–16. (in Polish with English summary)

Karasiewicz, T., Hulisz, P., Noryśkiewicz, A.M., Stachowicz-Rybka, R., 2019. Post-glacial environmental history in NE Poland based on sedimentary records from the Dobrzyń Lakeland. Quaternary International 501, A, 193–207. https://doi.org/10.1016/j.quaint.2017.10.039

Kerr, D.D., Ochsner, T.E., 2020. Soil organic carbon more strongly related to soil moisture than soil temperature in temperate grasslands. Soil Science Society of America Journal 84, 587–596. https://doi.org/10.1002/saj2.20018

Kobierski, M., Wojtasik., 2009. Organic and inorganic carbon densities in arable and orchard soils in selected mesoregions of the South-Baltic Lakeland. Roczniki Gleboznawcze – Soil Science Annual 60, 4, 57–64. (in Polish with English summary).

Kobierski, M., Kondratowicz-Maciejewska, K., Kociniewska, K., 2015. Soil quality assessment of Phaeozems and Luvisols from the Kujawy region (central Poland). Soil Science Annual, 66(3), 111–118. https://doi.org/10.1515/ssa-2015-0026

Kondracki, J., 2009. Geografia regionalna Polski. Wydawnictwo Naukowe PWN, Warszawa.

Konecka-Betley, K., Borek, S., Czarnowska, K., Kępka, M., Królowa, H., Łakomiec, I., Kobylińska, J., 1970. Effect of process of gleization from top on forming soils developed of boulder loam. Roczniki Gleboznawcze – Soil Science Annual 21(1), 21–50. (in Polish with English summary)

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of Köppen-Geiger Climate Classification updated. Meteorologische Zeitschrift 15, 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Krauss, M., Wiesmeier, M., Don, A., Cuperus, F., Gattinger, A., Gruber, S., Haagsma, W.K., Peigné, J., Palazzoli, M.C., Schulz, F., van der Heijden, M.G.A., Vincent-Caboud, L., Wittwer, R.A., Zikeli, S., Steffens, M., 2022. Reduced tillage in organic farming affects soil organic carbon stocks in temperate Europe. Soil and Tillage Research 216, 105262. https://doi.org/10.5167/uzh-217286

Kuźnicki, F., Skłodowski, P., 1979. Content of various forms of humus substances in pseudogleyed lessives soils with reference to the content of free iron and free aluminium. Roczniki Gleboznawcze – Soil Science Annual 30(2), 33–44. (in Polish with English summary)

Lal, R., 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123(1–2), 1–22. https://doi.org/10.1016/j.geoderma.2004.01.032

Loba, A., Waroszewski, J., Tikhomirov, D., Calitri, F., Christl, M., Sykuła. M., Egli, M., 2021. Tracing erosion rates in loess landscape of the Trzebnica Hills (Poland) over time using fallout and cosmogenic nuclides. Journal of Soils and Sediments 21, 2952–2968. https://doi.org/10.1007/s11368-021-02996-x

Loba, A., Zhang, J., Tsukamoto, S., Kasprzak, M., Kowalska, J., Frechen, M., Waroszewski, J., 2023. Multiproxy approach to the reconstruction of soil denudation events and the disappearance of Luvisols in the loess landscape of south-western Poland. Catena 220, 1–14. https://doi.org/10.1016/j.catena.2022.106724

Łabęda, D., Kondras, M., 2020. Influence of forest management on soil organic carbon stocks. Soil Science Annual 71(2), 165–173. https://doi.org/10.37501/soilsa/123321

Maia, S.M.F., Xavier, F.A.S., Oliveira, T.S., Mendonça, E.S., Filho, A.A., 2007. Organic carbon pools in a Luvisol under agroforestry and conventional farming systems in the semi-arid region of Ceará, Brazil. Agroforestry Systems 71, 127–138. https://doi.org/10.1007/s10457-007-9063-8

Marcinek, J., Komisarek, J., 1993. Przestrzenna ocena zawartości i zasobów materii organicznej w glebach w nawiązaniu do krajobrazów glebowych Wielkopolski (Spatial evaluation of soil organic matter content and its accumulation with reference to the Wielkopolska soil landscapes). Zeszyty Problemowe Postępów Nauk Rolniczych 411, 113–122. (in Polish with English summary)

Marcinek, J., Komisarek, J., 2004. Antropogeniczne przekształcenia gleb Pojezierza Poznańskiego na skutek intensywnego użytkowania rolniczego. AR. Poznań.

Markiewicz, M., Świtoniak, M., Bednarek, R., Gonet, S., 2014. Zasoby materii organicznej. [w:] Antropogeniczne przekształcenia pokrywy glebowej Brodnickiego Parku Krajobrazowego.[red.] Świtoniak M., Jankowski M., Bednarek R., Wydawnictwo Naukowe UMK, Toruń, 129–140.

Marks, L., 2012. Timing of the Late Vistulian (Weichselian) glacial phases in Poland. Quaternary Science Reviews 44, 81–88. https://doi.org/10.1016/j.quascirev.2010.08.008

Miechówka, A., Gąsiorek, M., Józefowska, A., Zadrożny. P., 2012. Carbon stocks in Little and Silesian Beskids soils agricultural use. Polish Journal of Soil Science. Soil Chemistry 55(2), 185–195.

Mroczek, P., 2018. Late Vistulian-Holocene Evolution of Loess Luvisols from the South Polish Uplands Recorded in Micromorphology. Wydawnictwo UMCS, Lublin, 109 pp.,

Muńoz-Rojas, M., Jordán, A., Zavala, L.M., De la Rosa, D., Abd-Elmabod, S.K., Anaya-Romero, M., 2012. Organic carbon stocks in Mediterranean soil types under different land uses (Southern Spain). Solid Earth 3, 375–386. https://doi.org/10.5194/se-3-375-2012

Musztyfaga, E., Kabała, C., 2015. Lithological discontinuity in Glossic Planosols (Albeluvisols) of Lower Silesia (SW Poland). Soil Science Annual 66(4), 180–190. https://doi.org/10.1515/ssa-2015-0035

Niewiarowski, W., 1959. Glacial forms and types of deglaciations on the moraine plateau of Chełmno (Bydgoszcz district). Studia Soc. Sci. Torun. Section C, 1, 4, Toruń. (In Polish with English summary).

Niewiarowski, W., Wysota, W., 1986. Moraine plateau levels of the Brodnica Moraine Plateau and their genesis. AUNC. Geography 19(60), 39–46. (in Polish with English summary)

Pietrzak, S., Hołaj-Krzak, J.T., 2022. The content and stock of organic carbon in the soils of grasslands in Poland and the possibility of increasing its sequestration. Journal of Water and Land Development 54(7–9), 68–7. 6. https://doi.org/10.24425/jwld.2022.141556

Pikuła, D., 2019. Praktyki zapobiegające stratom węgla organicznego z gleby. Studia i Raporty IUNG-PIB, 59, 13, 77–91. https://doi.org/10.26114/sir.iung.2019.59.06

Pińskwar, I., Choryński, A., Kundzewicz, Z.W., 2020. Severe Drought in the Spring of 2020 in Poland—More of the Same? Agronomy 10, 1646. https://doi.org/10.3390/agronomy10111646

Podlasiński, M., 2013. Denudation of Antropogenic Impact on the Diversity of Soil Cover and Its Spatial Structure in the Agricultural Landscape of Moraine; West Pomeranian University of Technology: Szczecin, Poland. (In Polish with English Summary)

Poeplau, C., Vos, C., Don, A., 2017. Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. Soil 3, 61–66. https://doi.org/10.5194/soil-3-61-2017

Poggio, L., de Sousa, L.M., Batjes, N.H., Heuvelink, G.B.M., Kempen, B., Ribeiro, E., Rossiter, D., 2021. SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty, Soil 7(1), 217–240, https://doi.org/10.5194/soil-7-217-2021

Polish Soil Classification (Systematyka Gleb Polski), 2019. Soil Science Society of Poland, Commission on Soil Genesis, Classification and Cartography. Wydawnictwo Uniwersytetu Przyrodniczego we Wrocławiu, Polskie Towarzystwo Gleboznawcze, Wrocław – Warszawa, 235 pp.

Porębska, G., Borzyszkowski, J., Gozdowski, D., 2021. Changes in organic carbon stocks in soils under Scots pine (*Pinus sylvestris* L.) stands in northern Poland over 26 years. Soil Science Annual 72(2), 140622. https://doi.org/10.37501/soilsa/140642

Radziuk, H., Świtoniak, M., 2021. Soil erodibility factor (K) in soils under varying stages of truncation. Soil Science Annual 72(1), 134621. https://doi.org/10.37501/soilsa/134621

Radziuk, H., Świtoniak, M., 2022. The Effect of Erosional Transformation of Soil Cover on the Stability of Soil Aggregates within Young Hummocky Moraine Landscapes in Northern Poland. Agronomy 12(11), 2595. https://doi.org/10.3390/agronomy12112595

Scharlemann, J. P.W., Tanner, E. VJ., Hiederer, R., Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Management 5(1), 81–91. https://doi.org/10.4155/cmt.13.77

Sewerniak, P., Markiewicz, M., Tarnawska, P., Marta, W., 2023. Environmental effects of a management method used after fire on development of temperate Scots pine ecosystem: a 15-year study from Poland. Environmental Management https://doi.org/10.1007/s00267-023-01843-8

Sinkiewicz, M., 1998. The Development of Anthropogenic Denudation in Central Part of Northern Poland; Nicolaus Copernicus University: Toruń, Poland. (In Polish with English Summary)

Solon, J., Borzyszkowski, J., Bidłasik, M., Richling, A., Badora, K., Balon, J., Brzezińska-Wójcik, T., Chabudziński, Ł., Dobrowolski, R., Grzegorczyk, I., Jodłowski, M., Kistowski, M., Kot, R., Krąż, P., Lechnio, J., Macias, A., Majchrowska, M., Malinowska, E., Migoń, P., Myga-Piątek, U., Nita, J., Papińska, E., Rodzik, J., Strzyż, M., Terpiłowski, S., Ziaja, W., 2018. Physico-geographical mesoregions of Poland: Verification and adjustment of boundaries on the basis of contemporary spatial data. Geographia Polonica 91(2), 143–170. https://doi.org/GPol.0115

Sosulski, T., Szara, E., Stępień, W., 2013. Dissolved organic carbon in Luvisol under different fertilization and crop rotation. Soil Science Annual 64(3), 114–119. https://doi.org/10.2478/ssa-2013-0015

Sowiński, P., Smólczyński, S., Orzechowski, M., Kalisz, B., Bieniek, A., 2023, Effect of Soil Agricultural Use on Particle-Size Distribution in Young Glacial Landscape Slopes. Agriculture 13, 584. https://doi.org/10.3390/agriculture13030584

Suuster, E., Ritz, C., Roostalu, H., Reintam, E., Kőlli, R., Astover, A., 2011. Soil bulk density pedotransfer functions of the humus horizon in arable soils. Geoderma 163(1–2), 74–82. https://doi.org/10.1016/j.geoderma.2011.04.005

Sykuła, M., Jankowski, M., Mendyk, Ł., Dąbrowski, M., Jasińska, J., Michalak, J., Michalski, A., Pindral, S., Bednarek, R., 2019. Wczoraj i dziś Mapy gleb Polski 1300 000 – próba adaptacji do Systematyki gleb Polski 2019 (SGP6). W 30. Kongres Polskiego Towarzystwa Gleboznawczego – Gleba źródłem życia, Bartmiński P., Dębicki R. (red.). Uniwersytet Marii Curie-Skłodowskiej w Lublinie, Lublin, 108–109.

Sytek, J., 1972. Humus content and its occurrence forms in soils lessives. Part I. Distribution of humus substances in soils lessives developed of sands and light loams. Roczniki Gleboznawcze – Soil Science Annual 23(1), 189–222. (in Polish with English summary)

Szopka, K., Kabała, C., Karczewska, A., Jezierski, P., Bogacz, A., Waroszewski, J., 2016. The pools of soil organic carbon accumulated in the surface layers of forest soils in the Karkonosze Mountains, SW Poland. Soil Science Annual 67(2), 46–56.

Szymański, W., Skiba, M., 2013. Distribution, morphology, and chemical composition of Fe-Mn nodules in Albeluvisols of the Carpathian Foothills, Poland. Pedosphere 23(4), 445–454. https://doi.org/10.1016/S1002-0160(13)60037-5

Świtoniak, M., 2006. Different pedogenesis conditioned by lithology of texture-contrast soils in Brodnica Lake District, in: Gierszewski, P., Karasiewicz, M. (Eds.), Ideas and practical universalism of geography. Geographical documentation. 32, 278–285. (in Polish)

Świtoniak, M., 2007. Ocena wartości ekologicznej gleb o dwudzielnym uziarnieniu w aspekcie zrównoważonego gospodarowania obszarami leśnymi Brodnickiego Parku Krajobrazowego (Assessment of the ecological value of soils with bipartite grain size in terms of sustainable management of forest areas of the Brodnica Landscape Park). [In:] Marszelewski, W., Kozłowski, L. [Eds.], Protection and development of Drwęca. UMK, Toruń, 335–344.

Świtoniak, M., 2008. Classification of young glacial soils with vertical texture-contrast using WRB system. Agrochimija i Gruntoznawstwo 69, 96–101.

Świtoniak, M., 2014. Use of soil profile truncation to estimate influence of accelerated erosion on soil cover transformation in young morainic landscapes, North-Eastern Poland. Catena 116, 173–184. https://doi.org/10.1016/j.catena.2013.12.015

Świtoniak, M., 2021. Rustification as a collateral process in clay-illuvial soils of northern Poland. Soil Science Annual 72(4), 143444. https://doi.org/10.37501/soilsa/143444

Świtoniak, M., Hulisz, P., Kałucka, I., Różański, S., 2011. Role of Scots pine monocultures on the formation of organic carbon resources in soils on an external dumping ground of the Bełchatów open-cast lignite mine. Roczniki Gleboznawcze – Soil Science Annual 62(2), 395–405. (in Polish with English summary)

Świtoniak, M., Dąbrowski, M., Łyszkiewicz, A., 2015. The Influence of Human-induced Erosion on the Soil Organic Carbon Stock in Vineyards of Fordon Valley. Polish Journal of Soil Science 48(2), 197–211.

Świtoniak, M., Mroczek, P., Bednarek, R., 2016. Luvisols or Cambisols? Micromorphological study of soil truncation in young morainic landscapes — Case study: Brodnica and Chełmno Lake Districts (North Poland). Catena 137, 583–595. https://doi.org/10.1016/j.catena.2014.09.005

Świtoniak, M., Michalski, A., Markiewicz, M., 2022. Classification of alluvial soils – problematic issues on the examples from South Baltic Lakelands, north Poland. Soil Science Annual, 2022, 73, 3, 157099. https://doi.org/10.37501/soilsa/157099

Tomczyk, A.M., Bednorz, E., 2022. Atlas klimatu Polski (1991–2020). Bogucki Wydawnictwo Naukowe. Poznań.

Uggla, H., Ferczyńska, Z., 1975. Studies on properties of rain-gley soils under deciduous forests in hilly areas of the Mazurian Lakeland. Roczniki Gleboznawcze – Soil Science Annual 26(1), 3–26. (in Polish with English summary)

USDA Natural Resources Conservation Service, 2008, Soil Quality Indicators. Bulk Density. Missouri.

Varnagirytë-Kabađinskienë, I., Ţemaitis, P., Armolaitis, K., Stakënas, V., Urbaitis, G., 2021. Soil Organic Carbon Stocks in Afforested Agricultural Land in Lithuanian Hemiboreal Forest Zone. Forests 12, 1562. https://doi.org/10.3390/f12111562

Wang, H., Wang, S., Yu, Q., Zhang, Y., Wang, R., Li, J., Wang, X., 2020. No tillage increases soil organic carbon storage and decreases carbon dioxide emission in the crop residue-returned farming system. Journal of Environmental Management 1, 261, 110261. https://doi.org/10.1016/j.jenvman.2020.110261

Waroszewski, J., Pietranik, A., Sprafke, T., Kabała, C., Frechen, M., Jary, Z., Kot, A., Tsukamoto, S., Meyer-Heintz, S., Krawczyk, M., Łabaz, B., Schultz, B., & Erban Kochergina, Y. V., 2021. Provenance and paleoenvironmental context of the Late Pleistocene thin aeolian silt mantles in southwestern Poland – A widespread parent material for soils. Catena 204, 1–13. https://doi.org/10.1016/j.catena.2021.105377

Wiesmeier, M., Barthold, F., Spörlein, P., Geuß, U., Hangen, E., Reischl, A., Schilling, B., Angst, G., Lützow, M.V., & Kögel-Knabner, I., 2014. Estimation of total organic carbon storage and its driving factors in soils of Bavaria (southeast Germany). Geoderma Regional 1, 67–78. https://doi.org/10.1016/J.GEODRS.2014.09.001

Wiśniewski, P., Märker, M., 2021. Comparison of Topsoil Organic Carbon Stocks on Slopes under Soil-Protecting Forests in Relation to the Adjacent Agricultural Slopes. Forests 12, 390. https://doi.org/10.3390/f12040390

Woronko, B., Karasiewicz, T.M., Rychel, J., Kupryjanowicz, M., Fiłoc, M., Moska, P., Adamczyk, A., Demitroff, M.N., 2022, A palaeoenvironmental record of MIS 3 climate change in NE Poland—Sedimentary and geochemical evidence. Quaternary International 617, 80–100. https://doi.org/10.1016/j.quaint.2021.08.012

Yitbarek, T., 2019. Carbon Stock of Luvisols as Influenced by Cropping System of Abela Lida, Southern Ethiopia. Agricultural Research and Technology 21(3), 556164. https://doi.org/10.19080/ARTOAJ.2019.21.556164

Zasoński, S., 1974. Micromorphological and chemical studies on the process of lessivage in fine sand soils. Part I. Loess soils of the Krakow Plateau. Roczniki Gleboznawcze – Soil Science Annual 25(3), 55–82. (in Polish with English summary)

Zasoński, S., 1979. Micromorphological properties and the chief pedogenetic processes of some soils on the weathering waste of the Wieliczka foothills. Roczniki Gleboznawcze – Soil Science Annual 30(2), 163–184. (in Polish with English summary)

Zasoński, S., 1981. Chief soil-forming processes on very fine sand rocks of the Wieliczka Foothills. Part I. General description of soils and some of their chemical properties. Roczniki Gleboznawcze – Soil Science Annual 32(2), 113–141. (in Polish with English summary)

Zasoński, S., 1983. Chief soil-forming processes on very-fine-sand rocks of the Wieliczka Foothills. Part II. Micromorphological properties. Roczniki Gleboznawcze – Soil Science Annual 34(4), 123–158. (in Polish with English summary)

Zomer, R.J., Bossio, D.A., Sommer, R., Verchot, L.V., 2017, Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. Scientific Reports 7, 15554. https://doi.org/10.1038/s41598-017-15794-8

Zwydak, M., Błońska, E., Lasota, J., 2017. Organic carbon accumulation in soil of different forest site types. Sylwan 161(1), 62−70.

Ocena zróżnicowania zasobów węgla organicznego w poziomach próchnicznych gleb płowych obszarów młodoglacjalnych Polski północnej

Słowa kluczowe

Gleby płowe
Erozja
Poziomy próchniczne
Klasyfikacja gleb
Właściwości stagnoglejowe
Ogłowienie gleb

Streszczenie

Gleby płowe (Luvisols, Retisols wg WRB) stanowią główny komponent pokrywy glebowej Polski. Ze względu na powszechność występowania i stosunkowo wysoką żyzność mają kluczowe znaczenie dla krajowej produkcji żywności. Rolnicze użytkowanie tych gleb prowadzi jednak do silnych przekształceń, a w wielu przypadkach do ich degradacji. Jest to szczególnie ważne w młodoglacjalnych krajobrazach morenowych Polski północnej. Intensywna rzeźba terenu w połączeniu z użytkowaniem rolniczym prowadzi do ogławiania gleb płowych, co może prowadzić do spadku zawartość węgla organicznego w glebie. Celem prezentowanej pracy jest ocena ogólnych zasobów węgla organicznego w poziomach ornych gleb płowych oraz ich zróżnicowania między najczęściej występującymi podtypami (wg Systematyki gleb Polski 2019). Badaniami objęto 72 profile glebowe. Średnie zasoby były stosunkowo niskie – 3.28 kg·m^{-2}, co można wiązać zarówno z uwarunkowaniami naturalnymi omawianych gleb, jak i silnymi przekształceniami antropogenicznymi. Pojedyncze „atrybuty podtypów”, choć wyrażają różnorodność gleb płowych, nie odzwierciedlają zróżnicowania zasobów próchnicy. Zasoby węgla organicznego różnią się jednakże statystycznie w poszczególnych podtypach określanych za pomocą maksymalnie dwóch najważniejszych atrybutów podtypów. Największe zasoby (4.12 kg·m^{-2}) odnotowano w glebach płowych próchnicznych stagnoglejowych (Stagnic Luvisols/Retisols) charakteryzujących się stosunkowo dużą wilgotnością i niewielkimi przekształceniami erozyjnymi. Gleby ogłowione (Ap-Bt-C(k)) zostały podzielone na dwa podtypy – erodowane próchniczne i erodowane (Haplic Luvisols). Podtyp zerodowany próchniczny odznaczał się dość wysokimi średnimi zasobami węgla – 3.61 kg·m^{-2}, drugi podtyp gleb erozyjnych miał wyjątkowo niskie wartości średnie – 1.40 kg·m^{-2}. Tak duże zróżnicowanie może wynikać z różnego tempa erozji w poszczególnych profilach oraz szczególnie w przypadku gleb płowych zerodowanych próchnicznych – regeneracyjnego, zrównoważonego zarządzania (np. uprawy pasowe, winnice, użytki zielone) prowadzącego do odbudowy zasobów próchnicy. Niskie zasoby (2.24 kg·m^{-2}) odnotowano także w glebach płowych typowych, których poziomy próchniczne również zostały zdegradowane przez erozję. Niewielkimi przekształceniami erozyjnymi i przeciętnymi zasobami – 3.57 kg·m^{-2} charakteryzował się podtyp gleb płowych dwudzielnych próchnicznych (Abruptic Luvisols / Haplic Planosols). Dalsze badania wymagają rozbudowy bazy danych. Ważnym aspektem jest również zasobność w węgiel organiczny głębszych poziomów genetycznych.