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Original Research

Sequestration of Humus Compounds in Soils of Northeastern Poland

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Abstract

Soil organic matter contains various organic compounds and plays an important role in the circulation of organic carbon (SOC) and affects the quality of soils. Soil carbon loss via soil erosion and slope processes results in SOC variations along the slope. Deposition of silt and clay on peat-muck soils protects them from mineralization of organic carbon compounds and release of CO_2 to ambient air. Slope processes occurring in northeastern Poland contribute to the reduction of SOC in eroded soils and sequestration of carbon in deluvial soils, mucky soils, and peat-muck soils. The pool of SOC and the lability of carbon can be used to assess the quality of soil in various conditions on the basis of the carbon management index (CMI). In the studied landscapes, the values increased down the slope and reached higher values in the soils covered with grasslands.

Keywords: carbon sequestration, deluvial soils, slope processes, humic and fulvic acids

Introduction

Northeastern Poland is a young glacial area shaped by glacier meltwater processes during the Pleistocene and Holocene epochs. It is distinguished by parallel variation of geological structure, relief, and soil cover [1]. In a relief of young glacial landscape, morainic landscape, and landscape of ice-dammed lakes occurs. In morainic landscapes a variety of hummocks and hills as well as mid-moraine depressions occupied by wetlands were formed as a result of glacial accumulation. In this type of landscape, ground moraine prevails [2]. Landscapes of ice-dammed lakes are less diversified. When the outflow of waters from the glacier had been blocked, silts and clay were accumulated in the vast lake of melted ice. The ridges of moraines are smooth and the wetlands occupy a small area.

Concave forms that accompany hills of various origin play an important role in the natural environment [3] – they are an ecological niche for various species of flora and fauna, can retain water and are specific filters for nutrients. Depressions accompanying the hills are the places of accumulation of various mineral and organic soil formations.

In northern Europe, during the postglacial period, processes of natural and anthropogenic denudations occurred with various intensities. They contributed to the mosaic soil cover and heterogeneity of soil formations [4]. Soil material was washed off, slipped from the slope and deposited in the depressions. Consequently, deluvial soils, mucky soils, and silted peat-muck soils were formed during the Holocene Epoch [5]. These soils have different morphology, clay fraction content, and chemical properties, as well as various amounts of soil organic matter (SOM) and humus compounds.

Soil organic matter (SOM) comprises various organic compounds and organisms living in the soil. SOM plays an important role in the circulation of organic carbon (SOC) and affects the quality of soils in relation to water retention capacity, cation sorption capacity, etc. [6, 7]. During slope processes occurring in the landscapes of northeastern Poland, the quality of soil on the top is diminished [8-10]. Soil components with the lowest size and lowest density are removed [11]. Consequently, soil formations occurring at

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lower parts of the slopes are enriched in clay, silt and organic matter (washed humus). Clay minerals may form stable forms with SOC. Clay and silt fractions, after deposition on organic soils, protect them against accelerated mineralization of organic matter. Soils rich in clay protect SOM from decomposition by stabilizing substances that bind to clay surfaces. Aggregation, enabled by the presence of clay, also protects SOM from microbial mineralization. Carbon loss via soil erosion results in SOC variations along the slope gradient. The major components of SOC are humic substances. They play an important role in chelation and complexing of ions and cations [12], influencing the removal of SOC by soil erosion [13]. Numerous studied have been carried out to describe soil erosion and soil organic matter balance. However, not much is known about the impact of soil erosion on catenal distribution and the ability of sequestration of humic and fulvic acids and labile forms of carbon in surface horizons in two basic types of landscapes in northeastern Poland: morainic and ice-dammed lakes. The emphasis should be put on the influence of carbon pools and the lability of carbon on soil quality. One indicator of soil quality is the carbon management index (CMI) proposed by Blair et al. [14]. It is closely correlated with physical, chemical, and biological soil properties [15], and can be a useful parameter to assess the quality of soil management systems.

The aim of this paper was to determine the amount of soil humus fractions in various types of soil and estimate soil carbon management indices in the catenas of landscapes of northeastern Poland.

Experimental Procedures

The study was carried in two landscapes typical for northeastern Poland – morainic and ice-dammed lakes. Four soil catenas were examined – two in each landscape. The soil types according to the World Reference Base [16] are given below. The Polish soil classification system [17] is more detailed and fitted to European soil conditions; therefore, Polish soils types also were presented (in brackets). In morainic landscape typical toposequences of soils were found. They consisted of eroded soils: Haplic Luvisols (lessive soils) and Calcaric Regosols (pararendzinas), which turned into Haplic Cambisols and Fluvic Gleysols (brown soils and shallow, medium deep and deep deluvial soils) in the middle and lower parts of the slope. At the bottom of the slope and in the depressions, Mollic Fluvisols and Haplic Histosols (shallow humous deluvial soils on peats and mucky soils, differently silted peat-muck soils) were formed. The depressions were closed (without outflow), with peatlands drained with open ditches. Slope gradient oscillated between 12% and 13% and the soils were used as grasslands. In the landscape of ice-dammed lakes the following soil sequence was noted: Gleyic Phaeozems (black earths) – Fluvic Gleysols (shallow proper deluvial soils) – Mollic Fluvisols (deep, medium deep and shallow humous deluvial soils on peat) – Haplic Histosols (mucky soils and peat-muck soils). The land was drained with drainage pipes and the soils were used as plowland. The soil erosion threat was low and the slope gradient was up to 7%.

In the laboratory, soil samples were air dried and visible plant remnants were removed by hand picking. For mineral fraction analysis, samples were sieved on 2 mm mesh and the percentage of fractions of diameter 50-2,000 µm (sand), 2-50 µm (silt), and <2 µm (clay) was determined using the Bouyoucos-Cassagrande method modified by Proszynski. SOM content was estimated on the basis of loss-on-ignition, which was determined after dry ashing of soil samples for 6 hours at a temperature of 550ºC. SOC content was measured with a spectrophotometer after oxidation with potassium dichromate [18], and total nitrogen (TN) was measured by the Kjeldahl method. Soil reaction was determined in H_2O and 1 M KCl potentiometrically, and cation exchange capacity (CEC) and base saturation (BS) were calculated based on exchangeable cation content in a solution after extraction with 1 M ammonium acetate (CH_3COONH_4, pH 7.0) [19].

For humic and fulvic acid extraction the scheme described by Duchaufour and Jacquin [20] was used. Humic substances fractioning was performed using three extraction solvents: a mixture of 0.1 M sodium diphosphate ($Na_4P_2O_7$) and 7.5% sodium sulphate (Na_2SO_4) at pH 7.0 used to extract the most free humus compounds, 0.1 M sodium diphosphate ($Na_4P_2O_7$) used to extract humus compounds bound to cations, and 0.1 M sodium hydroxide (NaOH) used to extract strongly bound humus compounds and those with high molecular weight. Five grams of soil were mixed with 100 cm^3 of 0.1 M $Na_4P_2O_7$ and 7.5% Na_2SO_4 and left for 24 hours. Then the solutions were centrifuged for 30 minutes at 4,000 rpm and filtered through qualitative paper filters (Eurochem BGD, diameter 150 mm). The next day, residue was washed with 100 cm^3 of 0.1 M $Na_4P_2O_7$ and left for the next 24 h, then centrifuged and filtered as described above. The residue was again washed with 0.1 M NaOH with a contact time of 24 h, then centrifuged and filtered. Humic acids (CH) were precipitated with 0.05 M sulphuric acid in an aliquot of 50 cm^3 of three extracts and then redissolved with 0.1 M sodium hydroxide to determine their carbon content with a spectrophotometer (Shimadzu UV 1201V) following oxidation with a solution of potassium dichromate ($K_2Cr_2O_7$). The part of humus was not extracted because heterogenous organic compounds, called humins and ulmins, are insoluble (part of humus tightly bound to clay minerals or colloidal iron hydroxide and aluminium hydroxide) and was called residuum (R).

Additionally, potentially oxidizable carbon content was estimated by the method described by Blair et al. [14]. Soil samples containing 20 mg of SOC and 50 ml of 0.0333 M potassium permanganate ($KMnO_4$) were mixed and shaken for 30 minutes on a BIOSAN PSU 20 multi-shaker. Then the solutions were filtered through glass filters and the change in $KMnO_4$ concentration was estimated using 0.05 M oxalic acid ($H_2C_2O_4$). On the basis of the change in $KMnO_4$ concentration the amount of C that oxidized was calculated. The amount of oxidized SOC is estimated to be

Table 1. General properties of the soil formations studied.

Soil horizon	Thickness of soil horizons	sand	silt	clay	pH (KCl)	CEC	BS	BS (Ca^{2+})
	[cm]	[%]				[cmol·kg^{-1}]	[%]	
Morainic landscape								
A	23	65	25	10	6.6-6.9	16.3	86.8	71.9
Ad	65	58	33	9	4.9-7.0	26.1	91.7	81.7
AO	29	40	54	6	5.9-6.5	62.5	91.8	86.3
Mtsz	26	n.d.	n.d.	n.d.	6.0-6.8	104.9	83.9	79.6
Mtz	33	n.d.	n.d.	n.d.	5.7-6.5	139.0	85.3	81.6
Landscape of ice-dammed lakes								
A	26	34	46	20	6.5-6.7	26.6	92.9	75.7
Ad	100	31	45	24	5.9-6.6	38.3	90.7	76.9
AO	28	22	50	28	6.5-6.8	76.4	97.1	87.3
Mtsz	32	n.d.	n.d.	n.d.	6.8-6.9	119.9	91.7	82.5
Mtz	29	n.d.	n.d.	n.d.	7.0-7.1	161.8	92.9	86.6

A – humus horizon of eroded soils, Ad – humus horizon of deluvial soils, AO – mineral-organic horizon of mucky soils, Mtsz – strongly silted muck horizons, Mtz – slightly silted muck horizons, n.d. – not determined

the labile carbon (CL) and the difference between the SOC and CL is assumed to be non-labile carbon (CNL). The carbon pool index (CPI) was calculated based on changes in SOC ($CPI=SOC_{sample}/SOC_{reference}$). The lability index (LI) was determined based on changes in the proportion of CL ($LI=L_{sample}/L_{reference}$, where L=CL/CNL). The LI and CPI indices were used to calculate the carbon management index (CMI) (CMI=CPI×LI×100).

The obtained results were analyzed statistically by applying correlation analysis, analysis of variance and Duncan's significance tests (for n=50, $P\leq0.05$). The analyses were conducted using Statistica 8.0.

Results

The thickness of humus horizons (A) in eroded soils amounted to 26 cm. In deluvial soils it varied between 24 and 100 cm and in the landscape of ice-dammed lakes deluvial sediments were thicker. Mineral-organic horizons (AO) of mucky soils had a thickness of 10-28 cm. In peat-muck soils, muck horizons were silted (Mtsz – strongly silted, Mtz – slightly silted) and up to 33 cm thick (Table 1). Soils of the landscape of ice-dammed lakes contained more silt and clay than the soils in morainic landscape. Also, the cation exchange capacity (CEC) and base saturation (BS) were higher (Table 1).

In studied soils, the amount of SOM in surface horizons increased toward the depression (Table 2). In eroded soils SOM amounts in morainic landscape and landscape of ice-dammed lakes were between 23 g·kg^{-1} and 33 g·kg^{-1}, respectively. Mean amounts of organic matter in deluvial soils were twice lower in morainic landscape than in the landscape of ice-dammed lakes, and the differences were statistically significant (Table 2). In mucky soils and silted peat-muck soils SOM was higher but varied among the landscapes. In morainic landscape these differences were statistically significant. In the landscape of ice-dammed lakes, the differences between slightly and strongly silted mucks were small and statistically insignificant.

Similarly to the amount of SOM, soil organic carbon and total nitrogen (TN) increased toward the center of the depression. The least amounts were noted in A horizons of eroded soils and the highest amounts in muck horizons of peat-muck soils. However, the share of SOC and TN in organic matter was inverse. The highest values were stated in eroded soils of both studied landscapes. The lowest amounts of organic carbon and nitrogen in SOM were noted in strongly silted mucks and slightly silted mucks, respectively (Table 2). The differences in the share of TN and SOC in SOM were statistically significant between humus horizons of deluvial soils and AO horizons of mucky soils, as well as between AO horizons and slightly silted mucks (Table 2). The SOC/TN ratio in humus horizons of eroded and deluvial soils, in AO horizons of mucky soils and in strongly silted mucks was narrow and amounted to 10-12.5. In slightly silted mucks it was wider, reaching a value of 17.6 in the landscape of ice-dammed lakes (Table 2). The differences in SOC/TN ratio were statistically significant between slightly and strongly silted mucks.

Based on solubility, the humus compounds were divided into three fractions: free humic (CH I) and fulvic acids (CF I), humus compounds bound to cations (CH II and CF

Table 2. Content of soil organic matter, soil organic carbon, and nitrogen.

Soil horizon		I SOM	II SOC	III TN	IV SOC	V TN	VI SOC:TN	VII SOM	VIII SOC	IX TN	X SOC	XI TN	XII SOC:TN	Significance of differences P=0.05
		g·kg^{-1}			% of SOM			g·kg^{-1}			% of SOM			
		Morainic landscape						Landscape of ice-dammed lakes						
1 A	MN	22.7	15.50	1.51	58.0	5.82	10.2	32.7	18.96	1.54	58.0	4.79	12.5	
	SD	8.4	3.8	0.05	0.03	1.25	2.1	0.75	4.4	0.3	0.05	1.1	2.5	
2 Ad	MN	28.9	18.55	1.70	58.0	5.6	10.6	61.3	36.99	3.50	58.0	5.69	10.5	I<VII, II<V
	SD	17.0	9.9	4.1	0.06	0.8	1.6	34.9	20.5	1.8	0.03	1.0	1.7	
3 AO	MN	159.2	74.82	6.83	50.9	4.6	10.9	179.0	90.57	9.15	49.9	5.0	10.0	III<IX
	SD	23.7	17.9	1.0	8.6	2.9	1.0	22.0	10.5	1.4	1.8	0.3	0.8	
4 Mtsz	MN	341.0	157.20	14.52	43.6	4.05	10.7	479.0	215.20	17.17	44.9	3.6	12.5	
	SD	93.5	48.3	3.7	8.2	0.4	1.4	26.9	22.3	0.3	2.1	0.3	1.5	
5 Mtz	MN	639.2	311.63	21.84	48.6	3.4	14.2	516.0	263.40	14.99	51.1	2.9	17.6	III>IX
	SD	76.3	50.3	2.2	3.0	0.3	1.3	8.0	3.11	0.04	0.2	0.5	0.3	
Significance of differences P=0.05		3<4<5	4<5 3<4	4<5 3<4	2>3 3>4	2>3	4<5	3<4.5	3<4	4>5 3<4	2>3 3>4	2>3 3>4	4<5 3<4	

MN – mean, SD – standard deviation, A – humus horizon of eroded soils, Ad – humus horizon of deluvial soils, AO – mineral-organic horizon of mucky soils, Mtsz – strongly silted muck, Mtz – slightly silted muck

II) and humus compounds strongly bound to metal ions and clay minerals (CH III and CF III). The amount of free humus compounds was least varied in the soils of the landscape of ice-dammed lakes and amounted to 5.5-11.5% of SOC (Table 3). The highest amounts were stated in mucky and deluvial soils. In the soils of morainic landscape the content of these humus compounds oscillated between 6.3-25.7% of SOC (Table 3) and was the highest in deluvial soils. Least amounts of CH I and CF I were stated in slightly silted mucks in both studied landscapes. Mean amounts of CHCF I in humus horizons of deluvial soils (Ad) and mucky soils (AO) as well as strongly (Mtz) and slightly (Mt) silted mucks in morainic landscape were higher than in the landscape of ice-dammed lakes. However, the differences were not statistically significant (Table 3). The content of humus compounds bound to cations (CHCF II) was lower than free humus compounds. In the landscape of ice-dammed lakes the CHCF II fraction was the highest in deluvial soils and in morainic landscape – in strongly silted mucks. Mucky soils contained lower amounts of this fraction and the differences between deluvial and mucky soils were statistically significant (Table 3). The amount of humus compounds strongly bound to metal ions and clay minerals was approximately twice higher than CHCF II. The most abundant in CHCF III were deluvial soils of both studied landscapes. Least amounts of this fraction were noted in slightly silted peat-muck soils in the landscape of ice-dammed lakes. The mean amount of this fraction in humus horizons of deluvial soils in both studied landscapes was statistically higher than in AO horizons of mucky soils. The difference between mucky soils in morainic landscapes and landscapes of ice-dammed lakes was also statistically significant. Similar relations were stated for the sum of CHCF II and CHCF III. The highest amounts of humus compounds bound to mineral fraction were noted in strongly silted mucks and in deluvial soils, whereas least amounts were stated in mucky soils (Table 3). The amount of organic matter that was not extracted (residuum) was higher in mineral-organic (AO) and organic (Mtsz, Mtz) horizons than in humus horizons (A and Ad). Mean content of R in deluvial soils was significantly lower than in mucky soils. Higher amounts of non-extractable humus were reported in the landscape of ice-dammed lakes.

In morainic landscape humic acids prevailed over fulvic acids in peat-muck soils and the CH/CF ratios in slightly silted mucks amounted to 1.4 and in strongly silted mucks to 1.2 (Table 3). The CH/CF ratios in deluvial and mucky soils were less than 1.0. In the landscape of ice-dammed lakes the highest CH/CF ratio was noted in strongly silted mucks and AO horizons of mucky soils. In deluvial soils and slightly silted peat-muck soils fulvic acids prevailed over humic acids (Table 3).

The content of labile carbon (CL) fraction and non-labile carbon (CNL) increased down the slope and was the highest in slightly silted mucks (Table 4). The amount of organic carbon not susceptible to oxidation (CNL) was positively correlated with humin content (r=0.852). The content of CNL fraction also showed significant positive correlation with SOC content (r=982). The lability index (LI) in morainic landscape was the highest in slightly silted mucks

Table 3. Humus compounds of studied soil formations.

Variable (% of SOC)		1 Ad	2 AO	3 Mtsz	4 Mtz	5 Ad	6 AO	7 Mtsz	8 Mtz	Significance of differences P=0.05
		Landscape of ice-dammed lakes				Morainic landscape				
CHCF I	MN	7.9	8.1	7.3	6.0	12.1	10.5	11.2	10.5	
	SD	1.0	2.0	1.5	0.2	5.0	3.4	4.9	2.6	
CH I	MN	3.6	4.4	4.2	2.6	5.9	4.9	5.7	6.0	3>4
	SD	0.7	1.4	0.6	0.1	3.4	1.4	2.3	0.8	
CF I	MN	4.3	3.7	3.1	3.4	6.1	5.7	5.4	4.6	2<6
	SD	0.6	0.6	0.9	0.1	1.7	2.1	2.8	1.9	
CHCF II	MN	7.8	5.7	6.5	3.2	7.0	5.5	9.1	8.7	1>2
	SD	1.8	1.0	1.9	0.8	2.1	1.1	4.1	2.1	
CH II	MN	3.5	2.6	3.9	1.2	2.9	2.3	4.8	5.0	
	SD	1.1	0.8	1.4	0.1	0.8	0.5	2.7	1.1	
CF	MN	4.2	3.1	2.6	2.1	4.1	3.2	4.3	3.7	1>2
	SD	1.1	0.4	0.5	0.8	1.5	0.6	1.5	1.1	
CHCF III	MN	16.1	13.0	12.5	7.1	15.3	11.3	13.5	14.6	1>2 3>4 2>6 5>6
	SD	2.3	0.8	1.0	0.8	2.2	0.5	9.2	2.8	
CH III	MN	7.3	6.6	7.9	3.3	7.2	5.4	9.1	8.4	3>4 5>6
	SD	1.1	1.5	1.0	0.5	1.1	1.0	5.8	1.2	
CF III	MN	8.8	6.4	4.6	3.9	8.2	5.9	7.8	6.2	1>2>4 5>6 7>8
	SD	1.9	0.9	0.9	0.4	1.4	0.7	4.0	1.7	
R	MN	68.3	73.2	73.8	83.8	65.6	72.9	62.9	66.2	1<2 3<4 5<6
	SD	3.0	3.7	3.1	1.9	6.8	3.9	16.8	7.2	
CH	MN	14.3	13.5	15.9	7.0	16.5	12.5	17.7	19.4	3>4
	SD	1.5	3.5	2.5	0.7	5.6	2.7	9.6	2.9	
CF	MN	17.2	12.9	10.4	9.3	18.7	14.7	16.1	14.4	1>2>3
	SD	1.9	1.2	1.5	1.2	4.2	4.1	6.9	4.4	
CHCF II+ CHCF III	MN	24.0	18.7	19.0	10.3	22.3	16.7	25.9	23.3	1>2 3>4 2>6 5>6
	SD	2.8	1.8	2.4	1.7	4.0	0.6	12.4	4.6	
CH I/ CF I	MN	0.8	1.2	1.4	0.8	1.0	0.9	1.2	1.4	1<2
	SD	0.2	0.2	0.3	0.1	0.2	0.3	0.3	0.5	
CH II/CF II	MN	0.9	0.8	1.5	0.6	0.8	0.7	1.1	1.4	2<3>4 3>6 4>9 6<7
	SD	0.3	0.2	0.2	0.1	0.2	0.1	0.3	0.2	
CH III/CF III	MN	0.9	1.1	1.8	0.9	0.9	0.9	1.2	1.4	2<3 3>4 3>7
	SD	0.2	0.4	0.4	0.1	0.1	0.3	0.4	0.2	

MN – mean, SD – standard deviation, A – humus horizon of eroded soils, Ad – humus horizon of deluvial soils, AO – mineral-organic horizon of mucky soils, Mtsz – strongly silted muck, Mtz – slightly silted muck

Table 4. Labile (CL) and non-labile (CNL) carbon and indices for the soils of studied landscapes.

Soil horizon	SOC	CL	CNL	Indices in relation to eroded (A) soil				Indices in relation to adjacent higher situated soil			
	g·kg⁻¹			L	LI*	CPI*	CMI*	L	LI**	CPI**	CMI**
Morainic landscape											
A	15.53	1.22	14.28	0.086	1.000	1.000	100	0.086	1.000	1.000	100
Ad	20.3	1.48	18.82	0.079	0.918	1.310	120	0.079	0.918	1.310	120
AO	74.8	6.06	68.74	0.088	1.028	4.826	495	0.088	1.119	3.685	412
Mtsz	140.5	12.93	127.57	0.101	1.181	9.065	1070	0.101	1.150	1.878	215
Mtz	311.6	30.23	281.37	0.107	1.252	20.103	2517	0.107	1.060	2.218	235
Landscape of ice-dammed lakes											
A	25	1.80	23.20	0.078	1.000	1.000	100	0.078	1.000	1.000	100
Ad	23.7	1.92	21.78	0.088	1.136	0.948	107	0.088	1.136	0.948	107
AO	81.7	5.80	75.90	0.076	0.985	3.268	321	0.076	0.867	3.447	298
Mtsz	210.6	14.95	195.65	0.076	0.985	8.424	829	0.076	1.001	2.578	257
Mtz	243.9	22.44	221.46	0.101	1.306	9.756	1274	0.101	1.325	1.158	153

CL, CNL, and SOC are mean values of analyzed samples; L (lability of carbon)=CL/CNL; CPI (carbon pool index)=$SOC_{sample}/SOC_{reference}$; LI (lability index) =$L_{sample}/L_{reference}$; CMI (carbon management index)=CPI×LI×100;
*reference is A soil horizon and samples are Ad, AO, Mtsz, Mtz horizons;
** reference is a horizon lying higher in relation to the sample

and the lowest in deluvial soils as compared to eroded soils located on the top of the slope. In the landscape of ice-dammed lakes, LI was the highest in strongly silted mucks and the lowest in mucky soils and slightly silted mucks. The carbon pool index (CPI) and carbon management index (CMI) increased down the slope, similarly to CL and CNL. However, when these indices are calculated in relation to the adjacent higher located soil, the values of the above indices are different. In morainic landscape, the highest lability index, carbon pool index, and carbon management index were stated in mucky soils. In the landscape of ice-dammed lakes, the LI was the highest in slightly silted mucks and CPI and CMI values, similarly to the soils in morainic landscape, in mucky soils (AO horizons).

Discussion

In the studied landscapes, the soil sequence in a catena was typical for the slopes of northeastern Poland: eroded soils (lessive soils, pararendzinas, or black earths) – deluvial soils – mucky soils and peat-muck soils in the depression. Losses of SOC during slope processes are considerable but often negligible [21]. In the studied soil catenas of two landscapes representing northeastern Poland the loss of SOC and reduction of the thickness of humus horizons in eroded soils were observed. This process should be regarded as particularly negative as it decreases the sequestration of carbon in the soil. However, the thickness of surface horizons of soils located lower at the slope was increased. The deposition of humus layer in lower parts of the slope resulted in increased SOC pools in deluvial and mucky soils. Translocation of eroded material contributed to siltation of peat-muck soils situated in the depression. It should be noted that erosion-induced changes in SOC resulted in modifications of soil quality due to changes in nutrient content, soil structure, aggregation, infiltration capacity, and agronomic productivity [13, 22]. On the other hand, slope processes may contribute to the burial of soil carbon [13] in lower situated soils and effective carbon sequestration.

It should also be noted that the SOC/TN ratios in the investigated soils were increasing toward the depression but did not vary much between humus horizons, mineral-organic horizons and strongly silted mucks. Generally, the average SOC/TN ratio in deluvial soils ranges between up to 12, and the SOC/TN ratio of slope soils is slightly lower at up to 11 [23]. However, in slightly silted mucks, located in a depression, the ratio was the highest. Generally, humus horizons have narrower SOC/TN ratios than organic soils – a result of the content of undecomposed organic compounds contained in organic soils [24].

The chemical fractionation applied in the study is a technique suitable for the study of SOM composition and has been widely used in recent years [25, 26]. The study revealed that the soils in the landscape of ice-dammed lakes contained less humic acids, fulvic acids, and more non-extractable organic compounds (R) than the soils in morainic landscape. The least varied was the content of "free", most labile humus compounds (CHCF I) in the landscape of ice-dammed lakes. In this landscape the water table was stable whereas in morainic landscape the dynamics of groundwater level oscillated in wide ranges [27].

Water table oscillations placed the soils under oxidizing conditions that favored the formation of soluble, labile humus compounds due to an increase of microbial activity [28]. Therefore the soils in morainic landscapes contained more CHCF I fraction.

Noteworthy is the fact that in the landscape of ice-dammed lakes deluvial soils were most abundant in humus compounds bound to mineral phase of soil (sum of CHCF II and CHCF III), which is the result of higher amounts of silt and clay in these soils. According to Schnitzer [29], humic acids in association with colloids form stable complexes and therefore in soils containing more clay and fine silt, the part of humus bound to minerals is high.

The CH/CF ratios of deluvial soils were below or around 1. In organic soils the ratio was higher. In morainic landscape, where soils are used as grasslands, the CH/CF ratios of the three investigated humus fractions were above 1.0. In the landscape of ice-dammed lakes, where soils are used as plowland, the CH/CF ratios of slightly silted mucks were considerably lower. Taking into consideration the CH/CF ratio, organic soils differ from mineral soils. In mineral soils, the CH/CF ratio is usually below 1.0 [6, 22]. In organic soils, this ratio is indicative of the maturity of SOM. The CH/CF ratio in excess of 1.0 suggests the stability of SOM. When it is around or below 1.0, it indicates a significant supply of plant debris as fulvic acids are the first product of the humification process [30].

The increasing content of the CL and CNL fractions in the soils down the slope is a result of deposition of humus from eroded soils. Eroded soils are "de-headed" [31] and declined in the studied organic carbon fractions. An increase in carbon lability in mucky soils and peat-muck soils of morainic landscape, as well as deluvial soils and slightly silted mucks in the landscape of ice-dammed lakes, suggests more intense organic matter transformation. It is also supposed that the content of the labile carbon fraction and carbon indices are dependent on the land use system [14] and, consequently, by the processes taking place in the soil. The carbon management index (CMI) was generally lower in the soils used as plowland (in the landscape of ice-dammed lakes) than in grassland soils (morainic landscape). The changes in the amount of carbon indicate the changes under various agricultural systems and by the CMI value it can be assessed whether the applied practices or processes occurring in the soil are declining or rehabilitating the soil [32].

Conclusions

Translocation of soil surface layers during erosion forms deluvial soils with thick humus horizons. Deposition of silt and clay on peat-muck soils protects them from mineralization of organic carbon compounds and release of CO_2 to ambient air. Slope processes occurring in northeastern Poland contribute to the reduction of SOC in eroded soils and sequestration of carbon in deluvial soils, mucky soils and peat-muck soils. In the studied landscapes with various land use systems the carbon management index increased down the slope and reached higher values in the soils covered with grasslands. Although soils used as grasslands contained less soil organic carbon than the soils used as plowland, their carbon management was better and promoted soil quality.

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