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ORIGINAL PAPER

CONTENT OF SELECTED ELEMENTS AND EXCHANGEABLE CATIONS IN SOILS DEVELOPED FROM GLACIO-LACUSTRINE SEDIMENTS OF SĘPOPOLSKA PLAIN (NE POLAND)*

Sławomir Smólczyński, Mirosław Orzechowski,
Barbara Kalisz, Paweł Sowiński

Department of Soil Science and Land Reclamation
University of Warmia and Mazury in Olsztyn, Poland

Abstract

There are soils in northern part of the Masurian Lakeland and the Sępopolska Lowland that developed from fine-grained, glacio-lacustrine sediments and are now used as arable land. The purpose of this study was to determine the content of macro- and microelements, exchangeable cations and cation exchange capacity of the soils in a catenary sequence. The following soil properties were determined: particle-size distribution, pH, content of total organic carbon and total nitrogen, total content of Ca, Mg, K, P, Na, Fe, Mn, Zn and Cu and that of exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, H^+, Na^+). According to the Polish Soil Classification (2019), the soils on the top and in the upper parts of the slope in the studied catena were Humic vertisols, while the middle and lover parts of the slope comprised proper humic colluvial soils, and in the depression there were Murshic soils. According to the IUSS Working Group WRB (2015), the identified soils are Haplic Vertisols (Aric, Hypereutric, Endostagnic), Haplic Phaeozems (Aric, Colluvic) and Haplic Phaeozems (Aric, Colluvic, Pachic), Histosols (Hemic, Murshic, Eutric) and Histosols (Hemic, Murshic, Eutric, Mineralic). In the analysed soil catena, the soil texture as well as the distribution of macro- and microelements (except sodium and phosphorus) showed small variability between soil units. The soil's particle-size distribution in the catenary sequence hardly varied. Contrary to moraine areas, there was no significant enrichment of colluvial soils with the clay and silt granulometric fractions. The main factors determining the distribution of macro- and microelements in the surface horizons of soils developed from clay is the process of vertilization and homogenization of soil material by mixing it during plowing. The amounts of exchangeable cations follow the order: $Ca^{2+} > Mg^{2+} > H^+ > K^+ > Na^+$, with the highest content of base cations, cation exchange capacity and the highest base saturation

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Paweł Sowiński, PhD DSc, Department of Soil Science and Land Reclamation, University of Warmia and Mazury in Olsztyn, Plac Łódzki 3, 10-727 Olsztyn, Poland, phone (48) 89 523 48 48, e-mail: pawel.sowinski@uwm.edu.pl

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in hemi-murshic soils. The research has confirmed the validity of distinguishing soils covered with mineral or mineral-organic sediments in the taxonomy of Polish soils.

Keywords: macroelements, microelements, sorption properties, catena, Vertisols, colluvial soils, mursh.

INTRODUCTION

There are specific glacio-lacustrine sediments accumulated in shallow ice-dammed lakes in the northern part of the Masurian Lakeland and in the Sępopolska Lowland (Morawski 2005). The sediments and soils that have developed from these deposits are characterized by a fine grain size and a high content of the clay fraction (< 0.002 mm) predominated by illite-smectite and smectite minerals (Długosz et al. 2009). Due to the occurrence of depressions of ice-dammed lakes origin, the relief of these areas is rather undulated than flat. In the light of some previous studies, soils developed from glaciolimnic sediments, under different relief conditions, are most often classified as Vertisols (Mollic, Eutric and Dystric), Gleyic Chernozems, Haplic Luvisols, Vertic Cambisols, Haplic Gleysols (IUSS Working Group WRB 2015, Orzechowski et al. 2018*a*,*b*). Owing to their high fertility, they are intensively used for agricultural purposes, mainly as arable land (Kabała et al. 2019).

The content of elements in soils depends on the origin of parent rock, particle-size distribution and mineralogical composition of the clay fraction (lithological factors), soil-forming processes (pedological factors), and land use (anthropogenic factor) (Łabaz, Kabała 2014, Orzechowski et al. 2014, Sowiński 2016, Długosz et al. 2018)

Natural and anthropogenic denudation processes in post-glacial landscape have resulted in the diversity of soil cover on various sections of the slopes and in the depressions. These processes proceed at a different pace, depending *inter alia* on the slope gradient and shape, as well as the soil texture and soil use. As a result, specific sequences of soils along a slope and in the vicinity have been created over a fairly small area (Frielinghaus, Schmidt 1991, Sowiński et al. 2016, Sowiński 2016). It was found that the location of soils in a relief is the factor differentiating their sorption properties and content of elements. Down the slope together with a simultaneous increase of organic matter, the cation exchange capacity and total exchange bases were increasing in soils, while deluvial and organic soils in the depressions were a site of the accumulation of macro- and microelements, which made them a biogeochemical barrier in the landscape (Smólczyński, Orzechowski 2010*a*,*b* Smólczyński et al. 2011).

Unlike in moraine areas, the properties of soils developed from glacio-lacustrine sediments are hardly recognized. Despite the fact that clayey soils are the least susceptible to water erosion, deluvial soils occur in the areas used for agriculture in the Sępopol Plain mesoregion (Orzechowski et al. 2018*b*), Therefore, the research on properties of soils developed from clay and heavy loams was undertaken.

The aim of the study was to analyze the distribution of macro- and microelements, and exchangeable cations in a catenary sequence in soils developed from glacio-lacustrine sediments which were modified by erosion.

MATERIALS AND METHODS

The research was carried out in the southern part of the Sępopolska Lowland, which has a slightly undulated relief. The exact location of the research site is in the village Troksy near Reszel (Figure 1). Denivelations in the catena were 6 m, and the slope gradient was 7.0%. 13 soil profiles were described along the transect and sampled for analysis. Three soil profiles were represented by Vertisols, four belonged humic colluvial soils, and five were classified as organic murshic soils (Polish Soil Classification 2019).

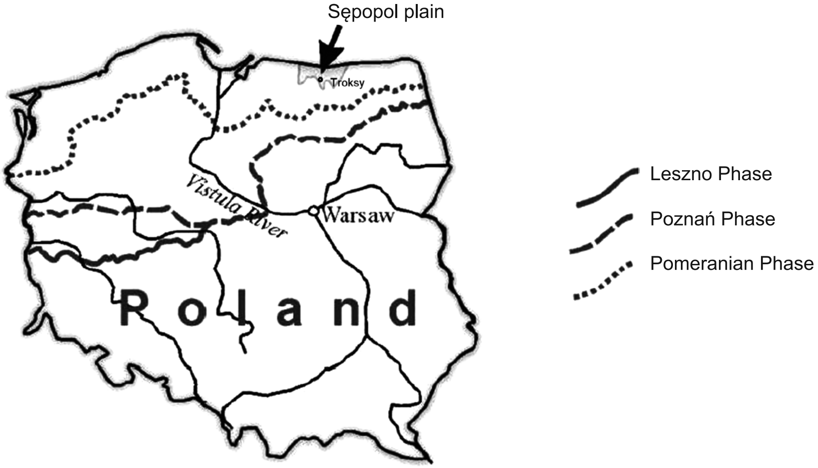

Fig. 1. Location of the soil catena

The following properties were analyzed in the collected soil samples: particle-size distribution of the fine earths (<2 mm) according to the laser diffraction method using a Mastersizer 3000; the soil texture classes were determined according to the classification of the Polish Society of Soil Science (*Particle*... 2009), pH was measured in H_2O and 1 M dm^{-3} KCl (1:2.5) potentiometrically, the content of total organic carbon (TOC) and total nitrogen (TN) was determined with a CN Analyser Vario Max Cube Elementar, the content of exchangeable base cations (Ca^{+2}, Mg^{+2}, K^{+}, Na^{+}) was measured in an extract of ammonium acetate (1 M dm^{-3}) of pH 7.0. Calcium and magnesium were determined by atomic absorption spectroscopy (AAS) on a Solaar 969 Pye Unicam spectrometer, whereas K and Na were determined by the flame emission method on a Flapho 4 spectrometer. The content of exchangeable hydrogen was determined in ammonium acetate solution (1 M dm^{-3}) in the case of mineral soils, or in barium chloride and triethanoloamine buffer solution with respect to organic soils. The cation exchange capacity (CEC), total exchange bases (TEB) and base saturation (BS) were calculated on the basis of the determination results.

Total concentrations of Ca, Mg, K, P, Na, Fe, Mn, Zn and Cu were measured by inductively coupled plasma optical emission spectrometry (iCAP 7400 ICP-OES Termo Scientific) after ultrawave mineralization (Ultrawave Milestone). Statistical calculations (mean, correlation coefficients, standard deviation) were carried out using Statistica 13.1. Principal component analysis (PCA) was applied to show relationships between the studied variables (Ca^{2+}, Mg^{2+}, Na^+, K^+, H^+, CEC, BS, pH (H_2O), pH (KCl), < 0.002 mm granulometric fraction, TOC, TN, Ca, Mg, K, Na, P, Fe, Mn, Zn, Cu). A dendrogram plotted according to the Ward method showed similarities between the analyzed soil horizons.

RESULTS AND DISCUSSION

Soils located on the top and in the upper parts of the slope in the studied transect, according to the Polish Soil Classification (2019), were classified as Humic vertisols and, according to the IUSS Working Group WRB (2015), they belonged to Haplic Vertisols (Aric, Hypereutric, Endostagnic). In the middle and lower parts of the slope, there were Typical humic colluvial soils (Polish Soil Classification 2019), and Haplic Phaeozems (Aric, Colluvic) and Haplic Phaeozems (Aric, Colluvic, Pachic) according to the WRB. These soils were underlain by reed peat (decomposition degree R2). In the depression, there were Murshic soils (Hemic, Murshic, Eutric Histosols and Hemic, Murshic, Eutric Histosols Mineralic soils according to the WRB). The thickness of humus horizons in Humic vertisols reached 42-48 cm. Humus horizons in humic colluvial soils had a thickness from 49 to 116 cm, and were underlain by medium-decomposed reed peat. Such thickness of colluvial deposits, which is found on arable, moraine areas of the Pomeranian and Masurian Lakelands (Braun 2011), indicates advanced anthropogenic denudation processes in the studied catena. Therefore, the conclusion expressed by Smołucha and Gotkiewicz (2002) about a slight threat of soil erosion to fine-grained soil formations (heavy loams and clays) in the landscape of ice-dammed lakes plains of north-eastern Poland is not confirmed.

The examined soils did not contain a coarse sand fraction (2-1 mm), and the average content of the coarse silt fraction was twice as low (12.3-16.5%) as that of fine silt (27.9 - 32.0%) – Table 1. The average content of the clay fraction in Ap horizons of Humic vertisols (21.7%) and humic colluvial soils

Table 1

Mean content of mineral granulometric fractions in the analysed soils

Soil horizon	Value	1-0.05	0.05-0.02	0.02-0.002	< 0.002
		(%)			
humic vertisols					
1 Ap	X	32.0	14.3	32.0	21.7
	S	3.5	0.6	0.0	2.9
	CV	10.9	4.2	0.0	13.4
2 A2	X	32.0	14.5	30.5	23.0
	S	0.0	0.7	2.1	2.8
	CV	0.0	4.8	6.9	12.2
3 C	X	19.5	12.3	29.3	39.0
	S	5.8	8.5	5.3	15.6
	CV	29.7	69.1	18.1	40.0
humic colluvial soils					
4 Ap	X	30.0	16.5	31.8	21.8
	S	7.8	2.6	3.2	6.9
	CV	26.0	15.8	10.1	31.7
5 A2	X	29.1	13.7	27.9	29.3
	S	6.4	3.2	4.1	6.4
	CV	22.0	23.4	14.7	21.8
Statistically significant differences *a* = 0.05		1>3; 2>3			

X – mean, S – standard deviation, CV – coefficient of variance

(21.8%) was similar, while in the parent material (C) of Humic vertisols it was almost twice as high (39.0%). The content of the sand fraction with a grain diameter of 1-0.05 mm in this horizon (19.5%) was statistically significantly lower than in the Ap horizon (Table 1). The Ap horizons of mineral soils had loamy texture, A2 horizons of vertisols and humic colluvial soils had the texture of clay loam, and C horizons of vertiols had clay, silty clay loam or heavy clay textures. It can be concluded that the textures in Ap and A2 of vertisols and humic colluvial soils hardly varied, while colluvial soils in rolling ground moraine areas were richer in clay and silt fractions than soils located in the upper parts of the slope and on the top.

Soil reaction in humus horizons (Ap and A2) of Humic vertisols and Humic colluvial soils ranged from slightly acidic to neutral (pH in KCl 5.9-6.7), in mursh horizons M it was close to neutral (pH in KCl 6.6-6.9), while in peat horizons (Oe) it was acidic (pH in KCl 4.8-5.7) – Table 2. The changes of soil reaction in a catenary sequence are related to the leaching of bases (Ebeid et al. 1995, Braun 2011).

The average carbon (23.0 g kg^{-1}) and nitrogen (1.7 g kg^{-1}) content in humus horizons of Humic vertisols was almost 2-fold lower than in humic colluvial soils, in which more carbon and nitrogen (48.6 g kg^{-1} TOC and 4.6 g kg^{-1} TN) was noted in A2 than in Ap horizons (respectively: 41.1 g kg^{-1} TOC and

Table 2

Basic properties of the soils

Soil horizon		C	N	C:N	pH	
		(g kg^{-1})			in H_2O	in KCl
Humic vertisols						
1 Ap	X	23.0	1.7	13.6	6.7-7.3	6.0-6.7
	S	5.9	0.5	0.7		
	CV	25.6	29.2	5.1		
2 A2	X	18.0	1.9	9.7	6.9-7.3	6.2-6.5
	S	2.5	0.2	0.1		
	CV	13.9	10.7	1.0		
Humic colluvial soils						
3 Ap	X	41.1	4.1	9.8	6.7-7.4	5.9-6.6
	S	18.7	1.6	1.8		
	CV	45.6	38.8	18.4		
4 A2	X	48.6	4.6	10.5	6.6-7.4	6.0-6.5
	S	34.9	3.4	1.6		
	CV	71.8	73.8	15.2		
5 Oe	X	390.7	24.6	16.4	5.8-6.1	4.8-5.7
	S	35.1	5.7	2.9		
	CV	9.0	23.5	17.7		
Murshic soils						
6 M	X	156.8	12.6	12.0	7.1-7.6	6.6-6.9
	S	74.0	3.2	3.2		
	CV	47.2	25.5	26.6		
7 Oe	X	375.9	20.2	18.9	5.8-6.0	5.2-5.5
	S	29.9	3.0	2.4		
	CV	7.9	14.9	12.7		
		4<5; 6<7	4<5; 6<7	1>2; 1>3; 4<5; 6<7		

X – mean, S – standard deviation, CV – coefficient of variance

4.1 g kg^{-1} TN) – Table 2. The research carried out by other authors indicates that there is a decrease in the content of organic carbon in eroded soils, which is an important factor for assessing the intensity of soil erosion, especially in soils rich in organic matter (LAL et al. 1999, EVE et al. 2002, LAL 2005, OLSON, JONES 2005, OLSON 2007, LIANG et al. 2009). This finding also indicates that the use of soils has a considerable impact on the carbon content. In Murshic soils, the average carbon content in the peat horizon amounted to 375.9 g kg^{-1}, and was 2.5-fold higher than in the mursh horizon (M). The lower content of carbon in the M horizon is the result of its silting with mineral material moving along the slope. In the immediate vicinity of humic colluvial soils, in the topsoil horizons of Murshic soils, the content of carbon decreased below 10%, and consequently murshes lost their character and were classified as mineral-organic sediments. Organic soils covered with mineral or mineral-organic sediments were distinguished as a separate subtype unit in the 6th edition of the Polish Soils Classification.

Table 3

Total content of elements in surface horizons of the soils

Soil horizon		Ca	Mg	K	Na	P	Fe	Cu	Zn	Mn
		(g kg^{-1})						(mg kg^{-1})		
Humic vertisols										
1 Ap	X	8.9	6.2	6.5	0.2	0.6	27.2	17.93	48.37	505.7
	S	1.3	0.5	3.6	0.0	0.3	0.8	2.8	1.3	40.7
	CV	14.6	8.1	55.4	0.0	50.0	2.9	15.6	2.7	8.0
2 A2	X	10.4	6.1	5.3	0.2	0.8	28.1	16.90	44.65	511.8
	S	3.2	0.4	3.6	0.0	0.2	0.9	3.3	1.6	22.3
	CV	30.8	6.6	67.9	0.0	25.0	3.2	19.5	3.6	4.4
3 C	X	14.7	9.1	7.1	0.2	0.6	38.0	21.15	53.90	576.6
	S	0.52	0.49	0.26	0.01	0.01	1.1	3.06	15.5	153.0
	CV	35.4	53.8	36.6	50.0	16.7	2.9	14.5	28.8	26.5
Humic colluvial soils										
4 Ap	X	12.9	5.9	8.3	0.3	1.0	25.7	18.53	53.78	470.6
	S	9.2	1.5	3.4	0.1	0.2	5.0	2.5	6.1	88.9
	CV	71.3	25.4	40.9	33.3	20.0	19.5	13.5	11.4	18.9
5 A2	X	9.0	6.0	8.1	0.3	1.3	28.5	24.61	60.27	357.5
	S	4.4	0.7	2.4	0.04	1.1	4.3	5.20	14.46	89.7
	CV	40.4	11.7	29.6	13.3	84.6	15.1	21.1	24.0	25.1
6 Oe	X	6.4	2.4	1.8	0.3	1.1	20.1	11.77	16.37	163.7
	S	5.0	0.9	0.1	0.1	0.8	0.2	2.50	2.96	11.9
	CV	78.1	37.5	5.6	33.0	72.7	1.0	21.2	18.1	7.3
Murshic soils										
7 M	X	36.6	5.8	5.2	0.4	1.8	21.0	21.09	51.56	528.1
	S	3.38	0.13	0.24	0.01	0.07	6.6	4.2	19.2	75.9
	CV	92.3	22.4	46.2	25.0	38.9	31.4	19.9	37.3	14.4
8 Oe	X	38.2	2.2	1.6	0.4	1.2	10.2	7.47	16.63	192.7
	S	15.9	0.8	0.9	0.1	0.7	8.9	6.5	10.0	86.1
	CV	41.6	36.4	56.3	25.0	58.3	87.3	87.0	60.1	44.7
Statistically significant differences $\alpha = 0.05$			7>8	7>8	1<4; 1<7; 4<7	1<4; 1<7; 4<7	7>8	7>8	7>8	7>8

M horizons of Murshic soils contained more calcium (36.6 g kg^{-1}), sodium (0.4 g kg^{-1}), phosphorus (1.8 g kg^{-1}), copper (21.1 mg kg^{-1}) and manganese (528.1 mg kg^{-1}) than did Ap horizons (Table 3). However, the differences were statistically significant only in the case of Na and P. In profiles of Murshic soils, surface horizons contained similar amounts of sodium, less calcium and significantly higher amounts of other elements than in horizons developed from peat (Oe). The research conducted by other authors indicates that the leaching of elements occurs during erosion and eroded soils are depleted in elements (Frielinghaus, Schmidt 1991, Cihacek, Swan 1994, Haygarth, Jarvis 1999, Farsang 2005, Ni, Zhang 2007).

The results indicate that, contrary to a catenary sequence in the moraine landscape, the distribution of macro- and microelements in the soil profiles of the analysed catena show low variability. Elements that can be translocated in a solution, like calcium and phosphorus, accumulate in hemi-murshic soils, located at the lowest parts of the studied relief, whereas, the content of elements translocated with soil fractions did not change significantly because the texture of soil material in surface horizons does not show significant variability. This relationship was confirmed by the statistically significant positive correlation between the clay fraction (<0.002 mm) and the content of Mg, K Fe, and Zn (Table 4). In addition, the content of the elements mentioned above depends on the content of organic matter. The content of Ca, P, Na was positively correlated with TOC, while the content of Mg, K, Fe and Zn was negatively correlated with this parameter (Table 4). It should be noted that the content of manganese and iron depends on oxidation-reduction conditions. Based on the distribution of various iron forms, Orzechowski et al. (2018) found that the soils developed from glacio-lacustrine sediments are young, showing poor weathering and not advanced release and leaching and therefore translocation of elements. An important factor determining the distribution of macro- and microelements in surface horizons of soils developed from clay is the process of vertilization. During shrinkage, fissures are created, into which material from the surface horizons may be moved. In addition, homogenization of soil material could have been facilitated by mixing it during plowing. Studies carried out so far in young glacial landscape, moraine and of ice-dammed lakes origin, have shown that accumulation of elements in soils of mid-moraine depressions occurs, and it may locally exceed the natural content (Smólczyński et al. 2004, Sowiński et al. 2016).

Exchangeable cations in the studied soils can be arranged as follows: Ca^{2+}> Mg^{2+}> H^{+}> K^{+}> Na^{+}. Peat horizons (Oe) contained more H^{+} than Mg^{2+}. In Ap horizons of Humic vertisols, the contents of Na^{+} (7.5 mmol (+) kg^{-1}) and K^{+} (12.2 mmol (+) kg^{-1}) were similar to the contents of these cations in the Ap horizon of Humic colluvial soils, while the contents of Ca^{2+} (259.8 mmol (+) kg^{-1}), Mg^{2+} (27.7 mmol (+) kg^{-1}), H^{+} 19.4 mmol (+) kg^{-1}), TEB (327.8 mmol (+) kg^{-1}) and CEC (327.2 mmol (+) kg^{-1}) were lower than in the Ap horizons of Humic colluvial soils (Table 5). However, the differences

Table 4

Correlation coefficients between the content of TOC, mineral particles and total content of elements

Properties	Ca	Mg	K	P	Na	Fe	Mn	Zn	Cu
0.05-0.02	-0.126	-0.596	-0.117	0.087	-0.093	-0.056	0.244	-0.363	-0.175
0.02-0.002 mm	-0.077	-0.390	-0.332	0.203	-0.035	-0.007	0.496*	-0.603*	-0.304
< 0.002 mm	0.540*	0.856*	0.445*	-0.040	-0.069	0.532*	-0.013	0.549*	0.317
TOC	0.849*	-0.391*	-0.351	0.673*	0.735*	-0.797*	0.290	-0.396	-0.017

* significance level at $\alpha = 0.05$

Table 5

Sorption properties of the soils

Soil horizon		Ca	Mg	K	Na	H	TEB	CEC	Ca	Mg	K	Na	H	BS
		(mmol(+) kg^{-1})							(%)					
Humic vertisols														
1 Ap	X	259.8	27.7	12.2	7.5	19.4	307.8	327.2	78.3	8.7	3.9	2.4	6.5	93.5
	S	94.5	3.4	2.8	0.3	4.1	96.3	93.5	5.7	1.3	1.5	0.6	2.5	2.5
	CV	36.4	12.3	22.9	4.0	21.1	31.3	28.6	7.3	33.3	38.5	25.0	38.5	2.7
2 A2	X	319.8	23.9	9.9	6.4	17.0	359.8	376.8	83.2	7.0	3.0	1.8	5.2	94.8
	S	157.5	1.2	2.1	1.1	1.4	155.4	154.0	7.8	3.2	1.8	0.4	2.4	2.4
	CV	49.2	5.0	21.2	17.2	8.2	43.2	40.9	9.4	45.7	60.0	22.2	46.2	2.5
3 C	X	574.0	41.0	9.1	6.2	8.4	630.3	638.6	88.9	6.8	1.6	1.1	1.7	98.3
	S	239.9	10.1	1.5	1.4	2.1	248.2	246.4	3.5	1.7	0.5	0.7	0.9	0.9
	CV	41.8	24.6	16.5	22.6	25.0	39.4	38.6	3.9	25.0	31.3	63.6	52.9	0.9
Humic colluvial soils														
4 Ap	X	498.8	36.8	9.7	9.2	26.7	554.8	581.5	81.0	8.0	2.4	2.1	6.4	89.2
	S	358.1	10.8	0.4	1.8	6.7	367.2	369.5	11.1	4.3	1.6	1.1	4.3	7.6
	CV	71.8	29.3	4.1	19.6	25.1	66.2	63.5	13.7	53.8	66.7	52.4	67.2	8.5
5 A2	X	383.7	49.4	10.4	9.5	26.3	454.3	480.5	78.6	10.6	2.3	2.2	6.1	94.0
	S	147.2	16.4	2.9	1.8	7.4	165.0	168.5	5.7	2.2	0.7	0.7	2.8	2.8
	CV	38.4	33.2	27.9	18.9	28.1	36.3	35.1	7.3	20.8	30.4	31.8	45.9	3.0
6 Oe	X	841.1	72.3	4.2	13.9	228.9	938.9	1167.8	72.1	6.8	0.3	1.2	19.6	80.4
	S	33.3	5.6	2.4	1.9	47.1	37.7	255.3	2.8	0.7	0.2	0.2	3.3	3.3
	CV	3.9	7.8	57.1	13.7	20.6	4.0	21.9	3.9	10.3	66.7	16.7	16.8	4.1
Murshic soils														
7 M	X	982.7	59.3	12.2	11.7	58.4	1080.9	1126.7	87.3	5.5	1.4	1.1	4.6	95.5
	S	431.3	18.5	8.4	4.0	45.0	442.8	476.3	2.0	1.0	1.5	0.4	1.9	1.8
	CV	43.9	31.2	68.8	34.2	77.1	41.0	42.3	2.3	18.2	107.1	36.4	41.3	1.9
8 Oe	X	865.8	80.7	4.7	15.9	245.8	972.8	1216.9	70.7	6.8	0.4	1.4	20.4	79.8
	S	216.4	26.4	1.0	2.9	53.4	219.2	255.3	4.7	2.5	0.1	0.4	3.0	3.1
	CV	25.0	32.7	21.3	18.2	21.7	22.5	21.0	6.6	36.8	25.0	28.6	14.7	3.9
Statistically significant differences $\alpha = 0.05$		1<7	1<7	7>8	7<8	7<8	1<7	1<7	1<7 7>8	1<7	1>7		7<8	7>8

were not statistically significant. Leaching of bases, particularly Ca^{2+} and Mg^{2+}, increases with the intensity of erosion (Ebeid et al. 1995). The differences in concentrations of cations and CEC in a soil profile sequence were also insignificant (between Ap and A2 horizons of Humic vertisols and Humic colluvial soils). The content of Ca^{2+}, Mg^{2+}, H^{+}, TEB and CEC showed positive correlation with the content of TOC (Table 6). Therefore, the highest content of base cations (TEB) and the highest cation exchange capacity were found in mursh horizons. In the M horizons, the content of Ca^{2+} was 3.5-fold, Mg^{2+} 2-fold, and H^{+}, TEB, CEC – three-fold higher than in the Ap horizons of Vertisols.

Base saturation in the topsoil ranged from 89.2% in Humic colluvial soils to 95.5% in hemi-murshic soils. The Ca^{2+} saturation was increasing in the catenary sequence from 78.3% in Ap horizons of Verisols to 87.3% in M horizons of Murshic soils. Saturation with Mg^{2+}, K^{+}, Na^{+} and H^{+} decreased in the catenary sequence, but the differences were not significant. In catenary studies of young glacial areas, base saturation was often high (Braun 2011, Sowiński et al. 2004). Distribution of Ca^{2+} H^{+}, and saturation with these cations in Murshic soils does not indicate the process of calcium leaching from the soil sorption complex, which has been found in these soils in delta, moraine and riverine landscapes (Smólczyński, Orzechowski 2010*b*).

The mean share of base cations in relation to total content of these elements was provided in Table 7. The share of magnesium cation amounted to 4.8-10.0% in mineral soil horizons of Humic vertisols and humic colluvial soils, while in Murshic soils it exceeded 50%. Sodium occurred mainly in exchangeable form (63.3 to 96.5%), and share of potassium cation ranged from 5.2% to 13.1%. More than half of calcium was in exchangeable form – in Murshic soils it varied from 50.6% in peat horizons to 76.0% in mursh horizons. The share of this cation in the studied soils was lower than in analogous soils in moraine and delta landscapes, where these values amounted up to 97.8% (Smólczyński Orzechowski 2010*b*).

The above relations between the studied properties were also confirmed by the principal component analysis (Figure 2), which revealed that the properties of the soils may be explained by two principal components – PC1 explained 41.62% of the data and PC2 explained 15.57% of the data. PC1 was positively correlated with Ca^{2+} (0.758), Mg^{2+} (0.921), Na^{+} (0.889), H^{+} (0.731), CEC (0.811), TOC (0.915), TN (0.901), Na (0.809), Ca (0.703), Cu (0.796) and Zn (0.708). PC2 was positively correlated with P (0.708) and negatively correlated with Mg (-0.682) and Fe (-0.771). The contents of the studied elements (except for P and Mn) and sorption properties (except for BS) were positively correlated with each other and with the content of TOC, but negatively correlated with pH.

Figure 3 presents a dendrogram which shows the similarity of the studied soil horizons in Vertisols, colluvial soils and mursh soils in the diversified relief of north-eastern Poland. Two major groups of horizons were distin-

Table 6

Correlation coefficients between the content of TOC, mineral particles and sorption properties

Properties	Ca^{2+}	Mg^{2+}	K^+	Na^+	H^+	TEB	CEC	Ca^{2+}	Mg^{2+}	H^+	K^+	Na^+	BS
0.05-0.02	-0.284	-0.338	0.151	0.162	0.303	-0.291	-0.280	-0.175	0.013	0.249	0.196	0.216	-0.355
0.02-0.002 mm	-0.200	-0.424	-0.396	0.055	-0.116	-0.223	-0.228	-0.035	-0.074	0.040	0.097	0.265	-0.199
< 0.002 mm	0.597*	0.437	0.051	-0.207	-0.354	0.600*	0.587*	0.491*	-0.300	-0.511*	-0.489*	-0.619*	0.346
TOC	0.919*	0.888*	-0.164	0.730*	0.908*	0.928*	0.926	0.475*	-0.530*	-0.058	-0.649*	-0.650*	0.112

* significance level at α =0.05

Table 7

Percentage of base cations in total content of the elements

Soil horizon		Ca	Mg	K	Na
		(%)			
Humic vertisols					
1 Ap	X	58.4	5.4	6.2	86.2
	S	16.9	0.4	1.5	3.4
	CV	28.9	7.4	24.2	3.9
2 A2	X	60.1	4.8	7.1	73.0
	S	12.0	0.5	2.1	12.2
	CV	20.0	10.4	29.6	16.7
3 C	X	81.6	6.1	5.6	63.3
	S	30.4	1.9	2.7	8.8
	CV	37.3	31.1	48.2	13.9
Humic colluvial soils					
4 Ap	X	77.7	7.5	5.4	84.2
	S	5.7	0.3	2.8	10.6
	CV	7.3	4.0	51.9	12.6
5 A2	X	72.1	10.0	5.2	85.5
	S	11.1	2.8	1.3	15.0
	CV	15.4	28.0	25.0	17.5
6 Oed	X	65.8	38.3	9.0	96.5
	S	15.6	9.2	4.7	3.5
	CV	23.7	24.0	52.2	3.6
Murshic soils					
7 M	X	76.0	13.8	10.6	67.8
	S	27.4	7.2	6.0	23.8
	CV	36.0	52.2	56.6	35.1
8 Oe	X	50.6	50.9	13.1	93.7
	S	18.2	22.3	4.2	6.7
	CV	36.0	43.8	32.1	7.2
Statistically significant differences α = 0.05			7<8		7<8

X – mean, S – standard deviation, CV – coefficient of variance

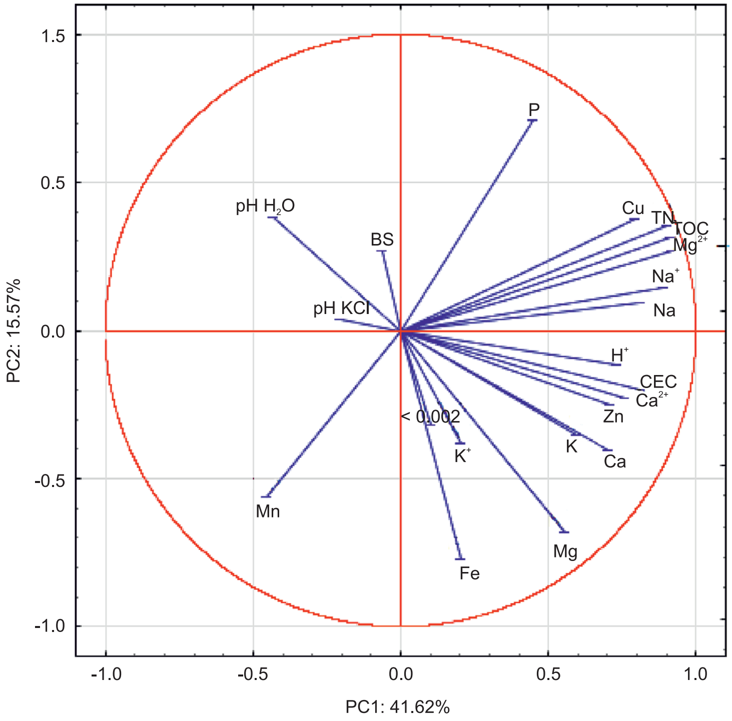

Fig 2. Principal component analysis

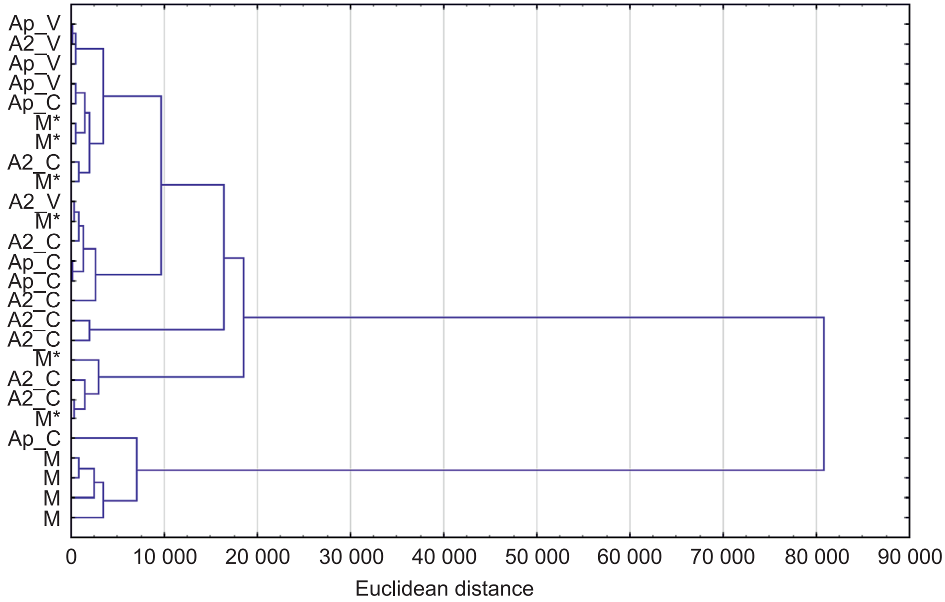

Fig 3. Dendrogram accordign to the Ward method

guished – the first group comprises mursh horizons developed from peat and not affected by translocation of soil material on the slope, and the second group comprises various soil horizons, but all affected by slope processes and siltation. In the second group, subgroups of Vertisols and Colluvial soils with admixture of M horizons of mursh soils can be distinguished.

CONCLUSIONS

1. Soil particle-size distribution in the catenary sequence was hardly diverse. Contrary to moraine areas, there was no significant enrichment of colluvial soils with clay and silt fractions.

2. The content and distribution of macro- and microelements (except for sodium and phosphorus) in the studied soils did not show significant differentiation between soil units.

3. Hemi-murshic soils, located at the lowest parts of the analyzed catena, were distinguished by the highest content of base cations, cation exchange capacity and the highest base saturation.

4. The study has confirmed the validity (purposefulness) of distinguishing organic soils covered with mineral or mineral-organic sediments in the taxonomy of Polish soils.

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