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VARIABILITY OF SOME PHYSICAL PROPERTIES OF LIMNIC RENDZINAS IN THE MAZURIAN LAKELAND (NE POLAND)

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Abstract. The variability of some physical properties of limnic rendzinas in the Mazurian Lakeland are discussed in the paper. For the study, six sites (68 soil carbonate samples) in NE Poland were examined in terms of their physical properties: total porosity, specific density, wet and dry bulk densities, volumetric and gravimetric water content. Moreover, the content of organic matter, $CaCO_3$ and non-calcareous fractions were also analysed to determine the type of soil calcareous sediments, and on this basis, three groups were isolated: calcareous gyttja, meadow limestone, lacustrine chalk. The highest values of specific and bulk densities were stated in lacustrine chalk, whereas the lowest ones – in calcareous gyttja. The highest total porosity was noted in calcareous gyttja, and the lowest one in meadow limestone. Lacustrine chalk and calcareous gyttja had the highest water content, and the differences between physical properties and soil calcareous materials were statistically significant. However, the differences between soil physical properties in surface soil horizons and calcareous materials were not statistically significant. Correlation coefficients showed that there were statistical dependencies between the examined soil properties, and the principal component analysis proved that soil physical properties were dependent mainly on organic matter.

Keywords: limnic rendzina, calcareous gyttja, meadow limestone, lacustrine chalk, soil properties

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INTRODUCTION

The soils developed from calcareous limnic materials (e.g. calcareous gyttja, lacustrine chalk, meadow limestone) were termed "limnic rendzinas" (subtypes: ordinary and chernozemic) in the Polish Soil Systematics, 6^{th} edition, and "Calcaric Fluvisols" and "Rendzic Phaeozems" (Limnic) in WRB systematics (Kabała *et al*. 2019, SGP 6 2019). These soils occur at the areas of former lakes. Since the end of the 9^{th} century, as a result of hydrotechnical works, many shallow lakes had been drained in order to increase the land for agricultural production in the Mazurian Lakeland (Lemkowska 2013ab, Lemkowska 2015, Lemkowska and Sowiński 2008, Lemkowska and Sowiński 2018, Łachacz and Nitkiewicz 2021, Uggla 1976).

Holocene calcareous limnic sediments are organic or mineral soil materials that were formed in the aquatic environment by the precipitation of carbonates from the solution, the deposition and processing of the carbonate remains of organisms, and the deposition of allochthonous organic matter. The criteria for the division of Holocene limnic sediments are based on the percentage of $CaCO_3$, organic matter and mineral non-carbonate fractions. The main component of carbonate limnic sediments is fine-grained calcite, which forms aggregates and differentiates the granulometric composition. It is accompanied by allogenic components (e.g. quartz, feldspars, clay minerals), autogenous (e.g. vivianite, gypsum, iron oxides, biogenic silica) and organic matter. These components and sedimentation conditions affect the physical and chemical properties of calcareous limnic materials (Bartkowiak 2010 and 2011, Brogowski *et al*. 2014, Damicz 2015; Dobak and Wyrwicki 2000, Jaroszewski 2015, Lemkowska 2013b, Żurek-Pysz 2011). An important factor differentiating the properties of limnic rendzinas is their use and anthropogenic transformation (Lemkowska 2013a, Łachacz and Nitkiewicz 2021, Nietupski *et al*. 2015).

Soils developed from limnic materials and soils in which limnic materials occur have untypical chemical and physical properties. These soils have an alkaline reaction and high saturation of the sorption complex with Ca cations (over 90%). The physical properties of these soils are related to the type of liming material and mineral admixtures from the catchment area. They are characterized by high total porosity (above 60%), bulk density below 1.0 $Mg \cdot m^{-3}$ and specific density of 2.3–2.4 $Mg \cdot m^{-3}$ (Jarnuszewski and Meller 2018, Jarnuszewski and Meller 2019, Uggla 1976).

The aim of this paper is to determine the contents and spatial variability of specific and bulk densities, water content, total porosity as well as their relationships with other soil properties. Vertical distribution of some physical properties in limnic rendzinas in the Mazurian Lakeland (NE Poland) is also discussed. Multivariate technique of PCA were used for the analysis of relationship between soil properties.

MATERIAL AND METHODS

The research was carried out at 6 sites, in 5 mesoregions of the Mazurian Lakeland (NE Poland) (Fig. 1). The studied sites are located at former lakes in moraine (Kruklin, Malinowo, Pęglity, Ustnik, Wynki) and outwash plains (Jęcznik) landscapes. They are used as arable lands and meadows, or are covered by wetlands or forests (Table 1).

Table 1. Coordinates and land-use types of study sites

Object	Coordinates (ETRS 89/ EPSG 2180)		Land use
	x	y	
Jęcznik	20.532323	53.365295	Meadow/forest
Kruklin	21.896755	54.027903	Arable land
Malinowo	20.348609	53.473073	Meadow
Pęglity	20.259867	53.722730	Arable land/meadow
Ustnik	20.698194	53.994308	Arable land
Wynki	20.126153	53.761915	Wetland

Fig. 1. Location of study area in mesoregions of Mazurian Lakeland

Thirty soil profiles and 68 samples were collected into steel rings of 100 cm^3 (Kopecky cylinders) and into plastic bags. In the collected material, the following properties were determined: organic matter (OM) as a loss-on-ignition (LOI) in a muffle furnace at a temperature of 550°C, the content of calcium carbonate (equivalent) by Scheibler volumetric method, soil pH by the potentiometric method in 1 mol·dm^{-3}KCl and in deionized H_2O. The content of mineral non-carbonate fractions (NCF) was calculated based on loss on ignition and the content of calcium carbonate. Specific density (SD) of mineral materials was determined using pycnometric method and SD of organic soils was calculated using the formula of Okruszko (1971): SD = 0.011x + 1.451, where *x* is the content of ash [%]. Wet bulk density (WBD), dry bulk density (DBD), volumetric water content (VWC) and gravimetric water content (GWC) were determined on a basis of weight-dry method using Kopecky cylinders, and total porosity (TP) was calculated on the basis of SD and DBD. The soils were classified according to the Polish Soil Classification, 6th edition (PSC 2019), same as soil horizon symbols (Kabała *et al*. 2019).

Three following groups of sediments were isolated, according to Polish Soil Systematics, 6th edition, on the basis of $CaCO_3$ content, NCF and OM: calcareous gyttja (≥20% OM and ≥20% $CaCO_3$), meadow limestone (<20% OM and ≥20% $CaCO_3$), lacustrine chalk (≥20% OM and ≥20% $CaCO_3$). 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 (WBD, DBD, TP, CWC, GWC and NFC, $CaCO_3$, OM).

RESULTS AND DISCUSSION

The mean content of organic matter in the surface horizons (Aca and Lcca) in studied soils amounted to 22.68% and was 3 times higher than its content in limnic materials Lm / Lcca (9.19%), lying deeper in the soil profile (Table 2). The differences were statistically significant. Statistically significant differences were also found between the mean content of OM in the analyzed soil formations (Table 3). The highest mean OM content was found in calcareous gyttja – 32.66%, and the lowest in lacustrine chalk – 8.62%.

Table 2. Physical properties of studied formations in limnic rendzinas

Properties	Value	Calcareous gyttja	Meadow limestone	Lacustrine chalk	Statistically significant differences $\alpha = 0.05$
SD $Mg \cdot m^{-3}$	X	2.19	2.37	2.46	1<2<3
	SD	0.18	0.05	0.06	
	CV	8.01	2.16	2.58	
WBD $Mg \cdot m^{-3}$	X	1.26	1.37	1.37	1<2<3
	SD	0.13	0.12	0.12	
	CV	10.40	8.95	8.62	
DBD $Mg \cdot m^{-3}$	X	0.62	0.81	0.74	1<2
	SD	0.21	0.18	0.15	
	CV	34.37	22.07	20.08	
TP %	X	72.15	63.75	70.09	
	SD	8.22	15.67	5.41	
	CV	11.40	24.59	7.72	
VWC %	X	62.85	58.25	63.53	2<3
	SD	12.90	6.50	8.82	
	CV	20.53	11.15	13.88	
GWC %	X	126.92	75.12	91.87	1>2<3
	SD	83.71	12.74	34.00	
	CV	65.96	16.95	37.01	
OM %	X	32.66	14.16	8.62	1>2>3
	SD	16.21	3.24	4.01	
	CV	49.64	22.90	46.55	
$CaCO_3$ %	X	46.04	63.10	88.36	1<2<3
	SD	13.11	16.06	5.16	
	CV	28.47	25.45	5.84	
NCF %	X	21.31	22.74	3.15	1>3, 2>3
	SD	9.15	16.19	2.71	
	CV	42.97	71.21	85.95	

Explanation of abbreviations: X – mean, S – standard deviation, CV – coefficient of variance, SD – specific density, WBD – wet bulk density, DBD – dry bulk density, TP – total porosity, VWC – volumetric water content, GWC – gravimetric water content, OM – organic matter, NFC – non-carbonate fractions.

The mean value of SD in humus horizons (Aca and Lcca) amounted to 2.29 $Mg \cdot m^{-3}$ and was statistically significantly lower than in limnic materials Lm / Lcca (2.45 $Mg \cdot m^{-3}$) (Table 2). In the studied soil formations, the mean values of SD were opposite to the OM content and amounted to 2.19 $Mg \cdot m^{-3}$ in calcareous gyttja, 2.37 $Mg \cdot m^{-3}$ in meadow limestone and 2.46 $Mg \cdot m^{-3}$ in lacustrine chalk, and the differences were statistically significant.

In the soil profiles (vertically), no significant differences were found for the dry bulk density. The mean DBD values in surface horizons amounted to 0.75 $Mg \cdot m^{-3}$ and were similar to the mean DBD values in Lm / Lcca horizons (0.74 $Mg \cdot m^{-3}$) (Table 2). Calcareous gytjja had the lowest mean DBD (0.62 $Mg \cdot m^{-3}$) among studied soil, and meadow limestone the highest mean DBD

(0.81 Mg · m^{-3}) (Table 3). These differences were statistically significant. On the other hand, the mean values of DBD in lacustrine chalk (0.74 Mg · m^{-3}) did not differ significantly from the mean DBD values in meadow limestone.

Table 3. Physical properties of studied surface horizons (Aca/Lcca) and limnic materials (Lm/Lcca)

Properties	Value	Aca/Lcca	Lm/Lcca	Statistically significant differences $\alpha = 0.05$
SD Mg · m^{-3}	X	2.29	2.45	1<2
	SD	0.15	0.08	
	CV	6.55	3.07	
WBD Mg · m^{-3}	X	1.32	1.37	
	SD	0.14	0.12	
	CV	10.51	8.56	
DBD Mg · m^{-3}	X	0.75	0.74	
	SD	0.23	0.14	
	CV	30.51	19.20	
TP %	X	66.27	70.01	
	SD	15.10	5.18	
	CV	22.79	7.39	
VWC %	X	59.33	63.44	
	SD	10.20	8.12	
	CV	17.19	12.80	
GWC %	X	95.14	91.41	
	SD	61.60	31.39	
	CV	64.75	34.34	
OM %	X	22.68	9.19	1>2
	SD	13.99	4.11	
	CV	61.69	44.76	
$CaCO_3$ %	X	54.97	84.90	1<2
	SD	17.22	10.62	
	CV	31.33	12.51	
NCF %	X	22.35	6.02	1>2
	SD	14.02	8.91	
	CV	62.73	148.04	

Explanation of abbreviations: see Table 2

Similar values of specific and bulk densities were stated by Uggla (1976), who explained the differences between groups of limnic sediments with admixtures of mineral fractions from the catchment area. Organic soils developed from limnic deposits in Western Pomerania had higher values of specific and bulk densities (Meller 2004, Jarnuszewski 2016, Jarnuszewski and Meller 2018) than the values in our study. The differences can be explained with the higher amount of non-carbonate fractions, simultaneous similar amount of $CaCO_3$ in parallel carbonate limnic deposits. Mean values of total porosity in the Aca and Lcca surface horizons (TP = 66.27%) were lower than in the parent material Lm / Lcca (TP = 70.01%; Table 2), which is typical for the studied soils. The differences, however, were not statistically significant. Additionally, there were no significant differences between the TP in the studied soil formations, which ranged from 63.75% in meadow limestone to 72.15% in calcareous gyttja (Table 3).

In other soils developed from limnic sediments, the values of TP were similar to the ones reported in our study, and were related to the content of non-carbonate fractions and $CaCO_3$ (Jarnuszewski 2016, Jarnuszewski and Meller 2018, Lemkowska and Sowiński 2008, Meller 2004). Uggla (1976) noticed that "clear" limnic calcareous deposits had very high TP values, whereas increasing admixtures of mineral fractions in limnic deposits make them more similar to humus horizons of mineral soils in terms of TP. Lemkowska (2013) suggested that the drying of the soil top layers led to a shrinkage of the limnic calcareous sediments and irreversible changes in colloids, and resulted in the decrease of TP in the topsoil.

The mean of wet bulk density values showed no vertical differences (1.32 $Mg \cdot m^{-3}$ in Aca and Lcca, 1.37 $Mg \cdot m^{-3}$ in Lm / Lcca), while the differences between mean WBD values in calcareous gytja – 1.26 $Mg \cdot m^{-3}$ meadow limestone 1.37 $Mg \cdot m^{-3}$ and lacustrine chalk – 1.37 $Mg \cdot m^{-3}$ were statistically significant. The average volumetric (VWC) and gravimetric (GWC) water contents did not show any significant differences vertically, in the soil profile (Table 2). However, there were differences between soil formations, i.e. the lowest mean VWC (58.25%) and GWC (75.12%) were stated in meadow limestone while the highest values of VWC (63.53%) in lacustrine chalk and the highest values of GWC in calcareous gyttja (126.92%).

Correlation coefficients in Table 4 show that there were statistical dependencies between the examined soil properties. The specific density was significantly positively correlated with $CaCO_3$, and negatively with OM and NFC. Similar dependencies were stated by Jarnuszewski and Meller (2018), especially for lacustrine chalk in NW Poland. The dry bulk density was negatively correlated with OM and positively with NFC. The total porosity was significantly negatively correlated with DBD. Specific density, wet and dry bulk densities (WBD and DBD) were positively correlated, and so were the contents of $CaCO_3$ as well as TP, VWC, GWC and OM. The value of OM and $CaCO_3$ or TP were negatively correlated.

Table 4. Correlation coefficients between the soil properties

	SD	WBD	DBD	TP	VWC	GVC	OM	$CaCO_3$	NFC
SD	1.000	0.539**	0.554**	-0.248	-0.338*	-0.691**	-0.953**	0.764**	-0.306*
WBD		1.000	0.740**	-0.493**	-0.003	-0.494**	-0.518**	0.293*	0.018
DBD			1.000	-0.885**	-0.556**	-0.799**	-0.540**	0.108	0.300*
TP				1.000	0.432**	0.546**	0.251	0.149	-0.429**
VWC					1.000	0.796**	0.339*	0.027	-0.321*
GWC						1.000	0.716**	-0.279*	-0.199
OM							1.000	-0.743**	0.236
$CaCO_3$								1.000	-0.825**
NCF									1.000

* significance level at $\alpha = 0.05$; ** significance level at $\alpha = 0.01$

Explanation of abbreviations: see Table 2

The principal component analysis showed that most of physical parameters in studied calcareous materials of limnic rendzinas were dependent mainly on organic matter (Fig. 2). The first principal component PC1 explained almost 50% of the total variability of data and was correlated with specific density (-0.931), dry bulk density (-0.872), wet bulk density (-0.750), gravimetric water content (0.923), organic matter (0.900), total porosity (0.726) and volumetric water content (0.708). The second principal component explained 30% of the total variance and was correlated with non-carbonate fractions (-0.854) and $CaCO_3$ (0.860).

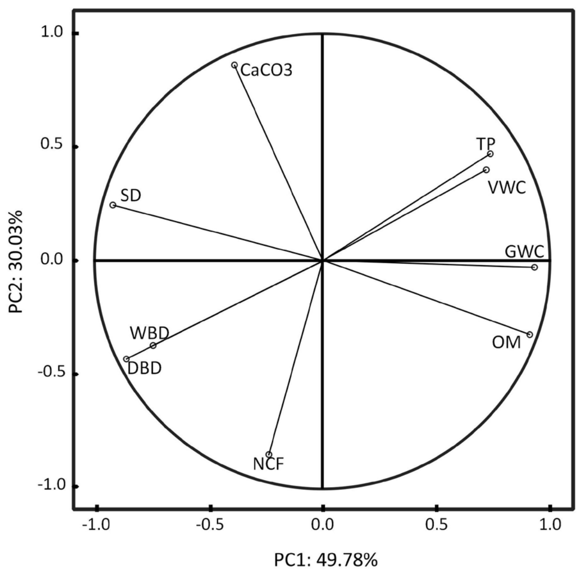

Fig. 2. Principal component analysis. Explanation of abbreviations: see Table 2

CONCLUSIONS

The land uses at six studied sites with limnic rendzinas (with high amounts of $CaCO_3$) were different, and so were the organic matter and mineral non-carbonate fractions contents. These enabled to classify studied soil materials as calcareous gyttja, meadow limestone and lacustrine chalk. Calcareous gyttja had the lowest values of specific and bulk densities and the highest values of total porosity. The highest water content was stated for lacustrine chalk and calcareous gyttja. The differences between physical properties and soil calcareous materials were statistically significant. However, there were no statistically significant differences between physical properties insurface soil horizons and calcareous materials. Correlation coefficients also showed that there were statistical dependencies between the examined soil properties. Specific and bulk densities were significantly positively correlated with $CaCO_3$ and negatively correlated with organic matter and mineral non-carbonate fractions. Total porosity was significantly negatively correlated with non-carbonate fractions. Water content was positively correlated with organic matter and negatively with $CaCO_3$ and NFC. The principal component analysis showed that the physical properties in limnic rendzinas were mainly dependent on organic matter.

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