

Evolution of shallow post-bog soils developed on Holocene carbonate sediments in NW Poland

Grzegorz Jarnuszewski , Edward Meller , Teodor Kitczak 

West Pomeranian University of Technology, Department of Environmental Management, Juliusza Słowackiego St, 17, 71-434 Szczecin, Poland

RECEIVED 14.09.2022

ACCEPTED 13.04.2023

AVAILABLE ONLINE 29.09.2023

Abstract: This research presents the characteristics and inferred evolution of post-bog soils developed in the Last Glacial Maximum area of northwestern Poland near the southern Baltic coast. The study involved a total of five sites near existing lakes in NW Poland. In total, 21 soil pits were described and sampled and 17 piezometers were installed. In soil samples chemical and physical properties were determined. During the hydrological year the water level was checked and chemical properties of water were determined, the floristic composition at each location was also carried out. Mineralisation of post-bog soils initiated by dehydration leads to the decomposition of organic surface layers and an increase in CaCO₃ content as well as mineral non-lime components at the expense of organic matter. A sequence of five soil types occurs in this landscape: Sapric Histosols (Limnic), Drainic Histosols (Calcaric, Limnic), Histic Gleysols (Murshic), Umbric Gleysols (Hyperhumic), Gleyic Phaeozems (Hyperhumic) that represent individual stages of soil genesis. Differences between the chemical properties of soils are apparent between organic vs organic-mineral and mineral layers. Man-induced drainage of post-bog soils changes their physical parameters. Bulk density increase and water retention decrease. The fluctuation of groundwater determines the moisture content of post-bog soils and affects the species composition of vegetation. Chemistry of groundwater is shaped mainly by the construction of catchment and the nature of its use, however, it is modified as a result of the inflow of macronutrients released during organic matter mineralisation processes and leaching of exchangeable forms from the sorption complex.

Keywords: decomposition of organic matter, dehydration, Gleysols, groundwater, Histosols, Phaeozems, plant communities, post-bog soils evolution

INTRODUCTION

The Vistula glaciation in Europe has left a young glacial landscape with numerous lakes and areas of biogenic (organic) accumulation. Natural succession of lakes, determined by climate, local hydrogeological conditions, and vegetation, has caused the transformation of some limnic environments into terrestrial-aquatic and terrestrial systems (Gierlowski-Kordesch, 2010; Kaiser *et al.*, 2012). In the present moderate climate, lake basins were initially infilled with mineral, then biochemical and organic deposits, which led to shallowing and even complete disappearance of the lakes (Kelts and Hsü, 1978; Freytet and Verrecchia, 2002; Schnurrenberger, Russell and Kelts, 2003). A specific type of sediment that fills the lakes is carbonate gyttja, which form are in areas of temperate climate where geological deposits composed of till and glacial fluvial are abundant in CaCO₃ (Kelts and Hsü,

1978; Meller, 2006; Kitczak *et al.*, 2014). Shallowing of the littoral zone of the lakes in connection with fluctuation of the water surface level enabled the accumulation of organic material and peat formation. The lowering of the water table was mainly caused by human activity (Piaścik and Gotkiewicz, 2004; Dawson *et al.*, 2010). In northern Poland, more than half of the Holocene lakes have undergone total “terrestrialisation”, this process has intensified since the end of the 19th century due to anthropogenic pressure associated primarily with local changes in the water (Łachacz, Nitkiewicz and Pisarek, 2009; Choiński *et al.*, 2012; Kaiser *et al.*, 2012). In northern Poland and north-east Germany, from 90 to 95% of bog areas have been transformed as a result of drainage or lowering the groundwater level in the catchment area (Ilnicki, 2002; Piaścik and Gotkiewicz, 2004; Gnatowski *et al.*, 2010; Cabezas *et al.*, 2012; Fell *et al.*, 2016; Wallor and Zeitz, 2016).

Lowering of the groundwater table associated primarily with the agricultural use of peatland areas leads to cessation of peat forming process and transformation of peat into muck (Gnatowski *et al.*, 2010; Wallor and Zeitz, 2016). Increasing oxygen diffusion intensifies mineralisation of organic material and causes changes in morphology, structure, as well as physical, chemical and biological properties referred to as “mucking” (Dawson *et al.*, 2010; Kechavarzi, Dawson and Leeds-Harrison, 2010; Verry *et al.*, 2011; Ewing *et al.*, 2012) and soil material is also referred to as mursh (Okruzsko, 1988) and this term will be used in this study.

The rate of organic soils degradation depends on many factors, the most important of which include groundwater depth, drainage period, land use, quality of organic material and climatic conditions (Dawson *et al.*, 2010; Gnatowski *et al.*, 2010; Brouns, Verhoeven and Hefting, 2014). Interruption of hydromorphic accumulation of organic matter and its mineralisation leads to settling and densification of the peat mass and reducing the areas of valuable peat habitats. Shallow organic soils are particularly exposed to rapid degradation and complete disappearance (Meller, 2006; Jarnuszewski, 2016). A key indicator of the organic soils degradation is their physical properties, which affect water retention capacity (Okruzsko, 1988; Verry *et al.*, 2011; Wallor and Zeitz, 2016). Chemical properties of soils also change, which directly translates into the nutrition and condition of plants (Könönen *et al.*, 2015). Moreover under aerobic conditions organic layer is decomposed leading to release of the greenhouses gases like CO₂, N₂O into atmosphere and carbon losses in range 0.27–1.98 kg·m⁻²·y⁻¹ depending on cultivation (Chimner and Cooper, 2003; Fell *et al.*, 2016).

Mineralisation of organic layers leads to loss of nutrients like nitrogen, phosphorus, organic carbon to groundwater and lakes, which causes deterioration of water quality in the lake and accelerates the eutrophication process (Geurts *et al.*, 2010; Cabezas *et al.*, 2012). In addition, climate change and the associated rise in temperature and extreme phenomena such as droughts, will accelerate the mineralisation process (Glatzel *et al.*, 2006) and shallow post-bog soils disappearance and restrictions of biodiversity (Jarnuszewski, 2015). This problem has been well recognised in temperate climates covering mainly Europe and North America (Geurts *et al.*, 2010; Cabezas *et al.*, 2012; Fell *et al.*, 2016). Only proper (extensive) use of post-bog soils and water level control will allow to preserve shallow soil habitats limit the adverse effects of their mineralisation.

The goal of this study was to characterise shallow post-bog soils developed on Holocene carbonate-rich sediments and the direction of their development. An attempt was also made to identify the relationships between changes in the properties of shallow carbonate soils and groundwater level and plant cover.

MATERIALS AND METHODS

STUDY SITES

The study involved a total of five sites near existing lakes (Fig. 1, Tab. 1), where limnic carbonate sediments occurred shallowly under organic material. Site 1 (14°37'31.650" E and 52°59'30.842" N) is an area of occurrence of limnic carbonate deposits near Strzeszowskie Lake, site 2 (14°50'15.205" E and 53°1'36.192" N) is near Sitno Lake, site 3 (15°45'20.851" E and 53°12'28.145" N) is

near Dubie Lake, site 4 is near Drawskie Lake (16°13'11.132" E and 53°34'45.696" N), and site 5 (15°26'39.685" E and 53°19'3.065" N) is near Sierakowo Lake. Study areas 1, 3 and 4 are in subglacial depressions filled mainly with mineral materials sands, and organic deposits, sometimes with clays. Site 1 is in moraine upland composed of clays and sands, site 3 is on an outwash plain with nearby hills of ground moraine, and site 4 is part of the marginal zone. Study area 2 is on a lake plain covered with biogenic accumulation deposits formed from in a flood plain, which is surrounded by a hummocky moraine plateau of sands, gravels and tills. Site 5 is in a small land reduction of the moraine upland made of sands and boulder clays.

The research study areas are usually used as permanent grasslands, or they are actually not used for agriculture. All study areas were previously drained, on some of them the maintenance of drainage facilities was abandoned. In the area of research facilities No. 1, 2 and 3, the multi-year average air temperature ranges from 8.2 to 8.5°C, while average precipitation ranges from 575 to 600 mm. For sites 4 and 5, the average temperature is 7.0 to 8.0°C and average precipitation from 600 to 700 mm (Kozmiński, Michalska and Czarnecka, 2007). Precipitation data from nearby measuring stations indicate that precipitation in 2011 was 625.5 mm for the Myślibórz station, and 706.7 mm for the Drawsko Pomorskie station (IMGW-PIB, 2023). Classification of precipitation conditions according to the relative precipitation index (RPI) (Kaczorowska, 1962; Gąsiorek and Musiał, 2011) indicate that year 2011 should be classified as an average year in terms of the amount of precipitation against the background of average multi-year data.

SOIL SURVEY

In total, 21 soil pits were described and sampled in years 2010–2011. Fifty one samples from surface horizons (O or A) were collected for chemical property measurements and 48 samples for physical properties determinations from organogenic layers. In soil samples, losses on ignition (LOI) value was determined by burning the material at 550°C for 4 hours in a muffle furnace after oven drying of the sample to constant weight at 105°C. The content of CaCO₃ by Scheibler method; based on the reported results, the share of mineral non-calcium fraction (Ncf) was calculated. Soil reaction (pH in 1M KCl and pH in H₂O) was determined potentiometrically. Organic carbon (C_{org}) was determined by method of Alten for organic layers or by Tiurin's method for mineral layers. Both methods based on oxidation of organic matter in K₂Cr₂O₇ with concentrated H₂SO₄. In Tiurin methods mixture of soil, K₂Cr₂O₇ and H₂SO₄ is boiling for 5 minutes and then tritration with Mohr's salt (ammonium iron sulphate) with the 2-(C₆H₅NH)C₆H₄COOH as indicators, while by Alten method mixture of soil sample, 2M K₂Cr₂O₇ and H₂SO₄ is heating in a water bath for 3 hours then tritration with Mohr's salt with the 2-(C₆H₅NH)C₆H₄COOH as indicator. Total nitrogen (N_{tot}) and sulphur content were determined by means of elementary analyser COSTECH ECS 4010. The content of soluble macronutrients (P, K, Mg, Ca, Na) – in a mixture (1:1) concentrated HNO₃ + HClO₄ acids. Content of phosphorus was determined colorimetrically, while the remaining components by using the atomic absorption spectrometer, type UNICAM SOLAAR 929. Quantities of exchangeable forms of such macronutrients as Ca, Mg, K, Na after soil extraction with

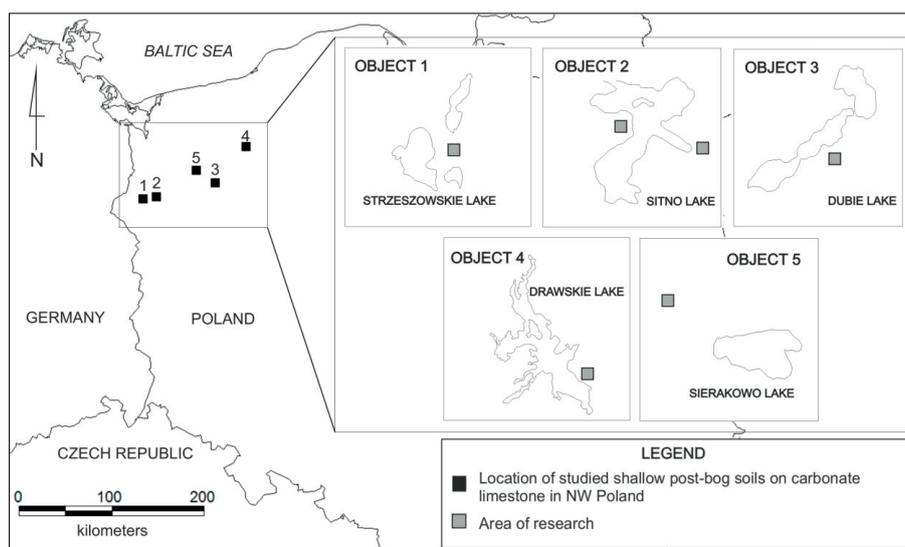


Fig. 1. Location of the study areas in northwest Poland; source: own elaboration

Table 1. Characteristics of research areas and nearby lakes

Specification		Value/feature for					
		1	2	3	4	5	
Lakes characteristics	name	Strzeszowskie Lake	Trzczańskie Lake	Sitno Lake	Dubie Lake	Drawskie Lake	Sierakowo Lake
	area ¹⁾ (ha)	127.2	16.0	186.0	120.4	1871.5	74.0
	average depth ²⁾ (m)	7.4	no data	3.5	7.3	82.2	no data
	max. depth ¹⁾ (m)	14.2		9.2	34.4	18.6	11.7
	current water table ²⁾ (m a.s.l.)	50.5	50.5	63.2	76.9	128.4	69.9
	type of lake	flow lake		flow lake	flow lake	flow lake	flow lake
	regulation of the water level	yes/damming		yes/damming	no	no	no
Groundwater level in 2011 (from piezometers) (m b.g.l.)	average	0.67	0.56	0.92	0.88	0.07	
	min.	0.17	0.03	0.18	0.71	0.00	
	max.	1.86	1.75	1.97	1.12	0.27	
	standard deviation	0.45	0.43	0.51	0.13	0.14	
Characteristics of the study area (soils survey)	area (ha)	59.4	32.1	13.3	17.5	9.0	
	average thickness of carbonate limnic deposits (m)	3.0 ³⁾	0.9	1.06	0.55	1.39	
	average thickness of organogenic layer (m)	0.39	0.34	0.37	0.32	0.51	
	use	wasteland/chalk mine/grassland	grassland/wasteland	arable land/wasteland	grassland	grassland	
	drainage	yes (ditches)	yes (ditches)	yes (ditches)	yes (ditches)	yes (ditches)	
	range of ordinates ⁴⁾ (soil research area) (m a.s.l.)	50.7–51.6	63.5–64.9	77.1–78.8	129.5–130.1	70.3	

¹⁾ Filipiak and Raczyński (2000).

²⁾ Choiński (2013).

³⁾ Based on System Gospodarki i Ochrony Bogactw Mineralnych “Midas” (PGI, 2022).

⁴⁾ Digital Elevation Model (GUGiK, 2022).

Source: own elaboration and literature data.

ammonium chloride at concentration of 0.5 mol·dm³. The specific density was determined by pycnometric method. The weight-drying method with the use of Kopecky cylinders (100 cm³ or 250 cm³) was applied to determine the bulk

densities, actual water capacity and capillary water capacity. Three samples (cylinders) were taken each soil horizon. The method based on weighing cylinders of known volume with fresh soil taken intact (actual water capacity), weighing cylinders after

drying in 105°C to constant weight (bulk density). Then the cylinders were partially immersed to achieve capillary penetration and weighed, and finally completely immersed to determine the total water capacity. The total porosity was calculated on the basis of the obtained specific density and bulk density. With a difference of general porosity and capillary water capacity were calculate the non-capillary (air) porosity.

WATER AND PLANT COVER SURVEYS

Near the soil pits, 17 piezometers were installed, in which the water level was checked 4 times (winter 2010, spring 2011, summer 2011, autumn 2011) during the hydrological year – 2011. The year 2011 was an average in terms of rainfall and water samples were taken for the determination of the reaction by electrometric method, total nitrogen using an automatic distillation apparatus, phosphorus – colorimetrically, and the remaining elements (Ca, Na, K, Mg) using the atomic absorption spectrometer. The assessment of the floristic composition used to determine the type of plant community was carried out in year 2011 using the botanical-weight method (Prończuk, 1962). The plant samples were mineralised in a 1:3 mixture of concentrated HNO₃ + HClO₄ acids and in this material were determined content of macronutrients (Ca, Na, K, Mg) by using the atomic absorption spectrometer and phosphorus colorimetrically according to Polish Norms (PN-ISO 11466 2002; PN-R-04014 1991).

STATISTICAL ANALYSIS

The obtained results were analysed using the STATISTICA 12.0 software (StatSoft 2014), in which the Pearson straight correlation coefficients were calculated and statistical tests were performed

for the probability coefficient $p < 0.05$. Data on the chemical properties of studied soils were subjected to logarithmic transformation to stabilise the variance between groups and to achieve a normal distribution. The distribution was verified using the Shapiro–Wilk test, and the homogeneity of variance using the Cochran, Hartley and Barlett C tests. Data that met the conditions were subjected to ANOVA analysis for the significance of differences with the Tukey post-hoc test for groups with unequal cardinality. Data not fulfilling the normal distribution condition were analysed for the significance of differences using the Kruskal–Wallis test, and in the case of unfulfilled homogeneity condition of variance, the Welch test was applied. In addition, PCA (Principal Component Analysis) factor analysis was performed to determine the relationship between values of selected soil, water and plant parameters in the study area.

RESULTS AND DISCUSSION

CLASSIFICATION AND LOCATION OF SHALLOW POST-BOG SOILS

The studied soils were classified using the World Reference Base for Soil Resources (FAO, 2015; Kabała *et al.*, 2019) into 5 second level categories: Sapric Histosols (Limnic), Drainic Histosols (Calcaric, Limnic), Histic Gleysols (Murshic), Umbric Gleysols (Hyperhumic), Gleyic Phaeozems (Hyperhumic). All soils were formed on such limnic carbonate-rich sediments as lake chalk or limestone gytija with a thickness of several centimeters to several meters, that were in a former littoral zone of a lake. The soils formed as shallow organics layers over limnic sediments (Fig. 2). The sequence presented in Figure 2 shows on the left a Sapric

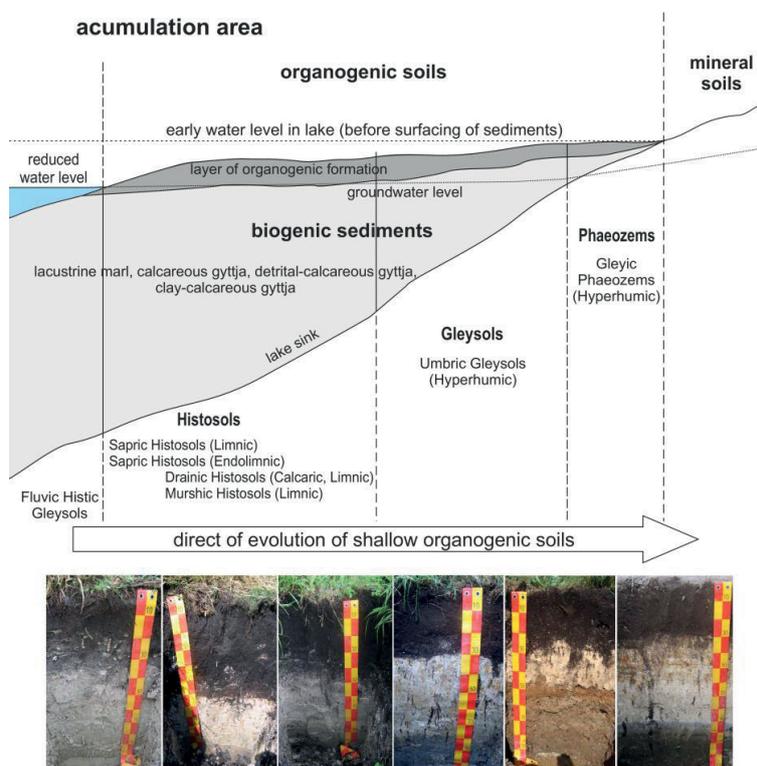


Fig. 2. Conception of evolution of shallow post-bog soils developed on Holocene Carbonate-rich limnic deposits; source: own study

Histosols (Limnic) with the degree of decomposition >H7 in von Post scale (PTG, 2019) which can be qualify as humified peat (Dawson *et al.*, 2010) or strongly decomposed peat (Okruszko, 1988; Glatzel, Lemke and Gerold, 2006). The studied peat soils developed in the shallow littoral lake zones under conditions of periodic flooding, where the peat-forming process took place. These soils are nearest the present water surface of functioning lakes, or at the lowest point of accumulation areas remaining after lakes decline, and thus are the most waterlogged. Natural and artificial lowering of water level in areas with organic soils (drainage with ditches) leads to dehydration of the peat and initiates decomposition. Subsequent soils that were identified during the study were severely murshed ones (affected by mucking process) due to the organic soil dehydration Drainic Histosols (Calcaric, Limnic), and murshic with a thickness of less than 0.40 m – Histic Gleysols (Murshic).

Progressive drainage and persistent low level of ground-water causes further, deeper transformations of the mursh and carbonate deposits beneath them which was found in objects 1, 2, 3, and 4. As a result of the progressive degradation, the organic formations are transformed into murshy forms represented in this work by Umbric Gleysols (Hyperhumic). In the last stage presented, mursh soils are transformed to mineral formations – Gleyic Phaeozems (Hyperhumic), which currently occur in the marginal zone of the original lake basin or on sediment elevations and for which the deepest depth of groundwater was found.

CHEMICAL PROPERTIES OF ORGANOGENIC LAYERS

According to Brouns, Verhoeven and Hefting (2014) and McCarter *et al.* (2020), the organogenic eutrophic soils, which should be include those in this study, contain small amounts of phenolic compounds as compared to oligotrophic peat, making them less resistant to dehydration and can stimulate their mineralisation after a week of drying. Fell *et al.* (2016) show that organic formations produced on carbonate limnic deposits are characterised by a slower loss of thickness than peat produced on clay or sand, however a long-term drainage of post-bog soils, similarly to other organic soils, allows diffusion of oxygen to surface layers and decomposition of organic matter. The change of anaerobic into aerobic conditions increases the biological activity of the soil: mesofauna, aerobic bacteria and fungi. Increasing the amount of soil fauna causes fragmentation of organic matter, which increases the surface area of aerobic bacteria and fungi interaction as a result of its accelerated

decomposition (Craft, 2001; Bothe, 2015; Säurich *et al.*, 2019). The described processes cause a significant reduction in the share of organic matter, the content of which is significantly related to the type of soil (Tab. S1).

In the least transformed Sapric Histosols (Limnic), the share of organic matter was 66.6%, and in the most transformed Gleyic Phaeozems (Hyperhumic), only 6.2%. The loss of organic matter in the studied soils is associated with an increase in the share of calcium carbonate and mineral non-lime parts. Statistical analysis showed that significant variation occurs in the content of calcium carbonate between peat soil and other inorganic soils, and in the case of Ncf, the variation was smaller (Tab. S1). Changes in the contribution of individual components entail the modification of chemical and physical properties of organogenic soils, which are often irreversible like reduction of total and capillary porosity (Verry *et al.*, 2011; Könönen *et al.*, 2015; Wallor and Zeitz, 2016) as demonstrated in this study. In the studied soils pH (from pH KCl – 5.81 in peat to pH KCl – 7.39 in Histic Gleysols) increase was associated with the increase in the percentage of CaCO₃. Carbon, nitrogen and sulphur are elements of organic matter, which confirms significant correlations between the presence of LOI and content of these elements in the studied soils (Tab. 2).

The process of organic matter mineralisation causes the release of C, N and S. In soils studied; there was 13 times less organic carbon, almost 10 times less total nitrogen and 14 times less sulphur in Gleyic Phaeozems (Hyperhumic) as compared to Sapric Histosols (Limnic). Losses of C and N in organic soils result from transformation of these elements accumulated in organic form by aerobic microorganisms activity and releases to the atmosphere mainly in the form of CO₂ and N₂O. However, it should be noted that the aerobic and anaerobic conditions in dewatering organic soils change over time as results of fluctuations in the groundwater level and different hydration depths of the organogenic materials. This leads to variable release of biogenic elements (C, N, P) into the soil solution and greenhouse gases emissions, including methane (Cabezas *et al.*, 2012; Brouns, Verhoeven and Hefting, 2014; McCarter *et al.*, 2020; Yli-Halla *et al.*, 2022; Offermanns *et al.*, 2023).

In organic soils, sulphur occurs mainly in organic form and is closely related to the content of C_{org} and N. The S content may also be influenced by the species composition of plants, the activity of microorganisms involved in S circulation in the soil, as well as the content of CaCO₃, the share of clay minerals, pH and mineral composition of minerals (Brouns, Verhoeven and Hefting, 2014). The research carried out indicates a relationship

Table 2. Correlation coefficients between CaCO₃, losses on ignition, non-carbonates fractions and macroelements and exchangeable bases content of organogenic layers of studied post-bog soils on Holocene carbonate limnic deposits in NW Poland (number of samples = 52)

Variable	C _{org}	N _{tot}	S	P	Ca	K	Mg	Na	Ca _{EB}	K _{EB}	Mg _{EB}	Na _{EB}	SEB
LOI	0.99*	0.96*	0.68*	0.24	-0.45*	-0.21	-0.54*	-0.02	0.73*	0.11	0.66*	-0.03	0.74*
CaCO ₃	-0.62*	-0.55*	-0.41*	-0.31*	0.80*	-0.08	0.85*	0.34*	-0.54*	-0.20	-0.28*	-0.21	-0.54*
Ncf	-0.52*	-0.55*	-0.37*	0.05	-0.32*	0.34*	-0.25	-0.34*	-0.30*	0.08	-0.49*	0.27	-0.31*

* Correlations significant at $p < 0.05$.

Explanations: LOI = losses on ignition, Ncf = mineral non-calcium fraction, EB = exchangeable bases of elements, SEB = sum of exchangeable bases. Source: own study.

between the content of organic matter (*LOI*) and sulphur in the tested soils (Tab. 2) In the organic soils content of P and K is related with organic matter and mineral composition of minerals. Generally content of these elements increased with progress of marsh-forming process and degree of organic matter decomposition (Dobrowolski *et al.*, 2010; Okupny *et al.*, 2016). Studied organogenic soils developed on carbonate sediments are characterised low P and K content due to the properties of the organogenic layers and the subsoil containing small amounts of minerals that are their main source. This dependence is confirmed by significant correlation of percentage Ncf share and K content in marsh soils (Tab. 2).

Increase in the content of general forms of Ca and Mg in the surface layers of studied soils was associated with the increase in the percentage of CaCO₃, which is confirmed by obtained significant correlation coefficients (Tab. 2). A significant correlation with CaCO₃ was also found in general Na content, the content of which was low in studied soils. This element, similarly to Ca and Mg, is easily leached from rocks that build the catchment and it gets into the lakes with flowing water creating limnic deposits or entering their composition (Kelts and Hsü, 1978). The content of Mg and Na in the carbonate sediments should be mainly associated with allogenic mineral material (Dobrowolski *et al.*, 2010; Okupny *et al.*, 2016). Among the analysed macronutrients, statistical analysis showed that significant differences occur in the case of C, N and Mg contents between peat and marsh layers and other inorganic soils. The Ca content in Gleyic Phaeozems (Hyperhumic) and the other types were also significantly different. In the case of K, P and Na contents, no significant differences were found between the soil types, while the Welch test showed that there are statistically significant differences between various types in terms of sulphur content.

The soils developed on carbonate sediments are distinguished by exchangeable hydrogen content and high saturation level of the sorption complex with alkaline cations reaching over 95% as well as wide Ca:Mg ratio (Łachacz, Nitkiewicz and Pisarek, 2009; Jarnuszewski, 2015).

In the studied soils, very high content of exchangeable form of Ca was found, which constituted 95% of the total sum of alkaline cations, the content of which in soils can be ranked similarly to that of Orzechowski, Smółczyński and Sowiński (2004), Meller (2006) and Łachacz, Nitkiewicz and Pisarek (2009) as follows: Ca > Mg > K > Na. The main source of exchangeable forms of Ca and Mg in studied soils is organic matter (significant correlation coefficients $r = 0.72$ and $r = 0.64$, respectively). Therefore, along with the decrease in the percentage of organic matter, sum of exchangeable cations clearly decreases, although leaching processes related to erosion and groundwater fluctuation also play an important role (Orzechowski, Smółczyński and Sowiński, 2004). The highest sum of exchangeable forms of Ca, Mg, K and Na cations was found in Sapric Histosols (Limnic), and value of this parameter decreased with the advancement of the mineralisation degree towards Gleyic Phaeozems (Hyperhumic) – Table S1. Exchangeable Na was outside the range of quantification in majority of samples. The increase in the percentage of CaCO₃ in the surface layers of studied soils causes the increase in the ratio of the total Ca and Mg content to the content of these elements in the exchangeable form from Sapric Histosols (Limnic) towards Gleyic Phaeozems (Hyperhumic).

Such a clear relationship was not observed in the case of potassium. The narrowest ratio of general K form to its exchangeable form was found in peat soils, while the widest in Histic Gleysols (Murshic). This differentiation may result from different mineral composition of the separated group in the form of mineral non-lime parts (Ncf). In the case of exchangeable Ca and the sum of exchangeable cations, organic and mineral soils of Umbric Gleysols (Hyperhumic) and Gleyic Phaeozems (Hyperhumic) types, significantly differed.

PHYSICAL PROPERTIES OF ORGANOGENIC LAYERS

In addition to differences in chemical properties resulting from the progressive degradation of shallow organogenic soils, significant changes can also be observed in physical properties and the structure. Peat subjected to the marsh forming-process delaminates into sublevels differing in structure, and the thickness of the organic layer decreases (Dawson *et al.*, 2010; Könönen *et al.*, 2015; Fell *et al.* 2016; Yli-Halla *et al.*, 2022). As the marsh forming-process progresses and the contribution of individual components of the solid phase changes, specific and bulk densities increase as well as the total and capillary porosity decreases (Meller, 2006; Kechavarzi, Dawson and Leeds-Harrison, 2010; Verry *et al.*, 2011; McCarter, 2020). The lowest specific and bulk density was recorded in peat, the tested mucks showed higher values of both parameters (Fig. 3); significantly higher specific and bulk densities were found in marsh formations. Changes in specific and bulk density are caused by the change in peat and marsh structure, as well as due to the decrease in the share of organic matter in studied soils.

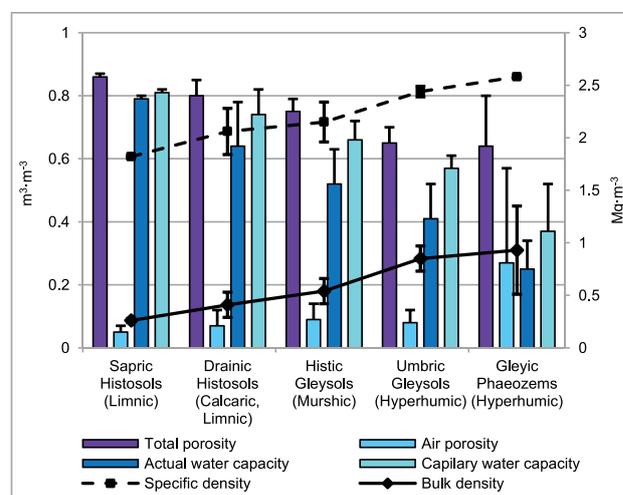


Fig. 3. Physical properties of organogenic layers of studied post-bog soils on Holocene carbonate limnic deposits in NW Poland; source: own study

The significant correlation coefficients determined for the surface layers of the studied soils (Tab. 3) clearly confirm the dependence of specific and bulk density on organic matter determined as *LOI* which is also confirmed by research Collins and Kuehl (2001) and Oleszczuk and Truba (2013). The percentage of mineral non-lime parts and CaCO₃ also significantly affected the values of both densities, however, this relationship was inverse and weaker than in the case of organic matter.

The consequence of the progressive mineralisation of the organogenic levels is the reduction of total and capillary porosity –

Table 3. Correlation coefficients between CaCO₃, losses on ignition, non-carbonates fractions and physical properties of organogenic layers of studied post-bog soils on Holocene carbonate limnic deposits in NW Poland (number of samples = 48)

Variable	Specific density	Bulk density	Total porosity	Air porosity	Actual water capacity	Capillary water capacity
LOI ^d	-0.99*	-0.82*	0.75*	-0.26	0.68*	0.74*
CaCO ₃	0.57*	0.30*	-0.21	0.06	-0.06	-0.19
Ncf	0.44*	0.56*	-0.57*	0.21	-0.66*	-0.58*

* Correlations significant at $P < 0.05$.
 Explanations: LOI and Ncf as in Tab. 2.
 Source: own study.

Figure 3 (Collins and Kuehl, 2001; Dawson *et al.*, 2010; Oleszczuk and Truba, 2013). In the case of studied soils, this dependence is confirmed by significant relationship between the organic matter content and mineral non-lime parts and the total and capillary porosity (Tab. 3). As the post-bog soils degrade, the ratio of mesopores to macropores drastically changes. The expression of these changes is the ratio of the capillary water capacity to the air porosity, which in Sapric Histosols (limnic) is over 16, while in Gleyic Phaeozems (Hyperhumic), it is less than 1.4. In addition, there is a noticeable reduction in the current moisture content of the organogenic layers along with decomposition rates (Tab. 3, Fig. 3). The actual moisture content depends mainly on the depth of groundwater level, which plays a decisive role in the rate of organic material degradation. The depth of dehydration is very

important, because carbonate sediments underlying organogenic layers are also transformed as a result of drying, which additionally may deepen the water deficit of surface layers (Marcinek and Sychalski, 1998).

PLANT COMMUNITIES

The investigated post-bog soils were mostly overgrown with grasses and herbaceous plants and they constituted the utility grasslands, or the area where meadow use has been abandoned. Area of occurrence of Gleyic Phaeozems (Hyperhumic), where the groundwater was deepest, was covered with ash-alder forest. The type of omit plant communities in non-forested areas was associated primarily with the depth of groundwater retention and frequency of use (Kitczak *et al.*, 2014; Bothe, 2015; Wallor and Zeitz, 2016). Wołejko, Herbichowa and Potocka (2005) and Łachacz, Nitkiewicz and Pisarek (2009) who emphasise that plant communities on this type of soil are unstable and express the stages of succession caused by the depth of occurrence of the average groundwater level and its fluctuation, nutrient availability, depth of organogenic levels and the performance method. In areas, where groundwater was shallow, species associated with wet conditions dominated, such as *Carex acuta*, *Phalaris arundinacea* and *Deschampsia caespitosa* (Łachacz, Nitkiewicz and Pisarek, 2009; Kitczak *et al.*, 2014; Wallor and Zeitz, 2016). Peat soils were dominated by *Carex acuta* and *Phalaris arundinacea* (Fig. 4), whereas in the area where Umbric Gleysols (Hyperhumic) occurred, where groundwater was found by 38 cm deeper on average, the dominant species was *Carex acuta*. Plant communities of the *Deschampsia caespitosa* type, also associated

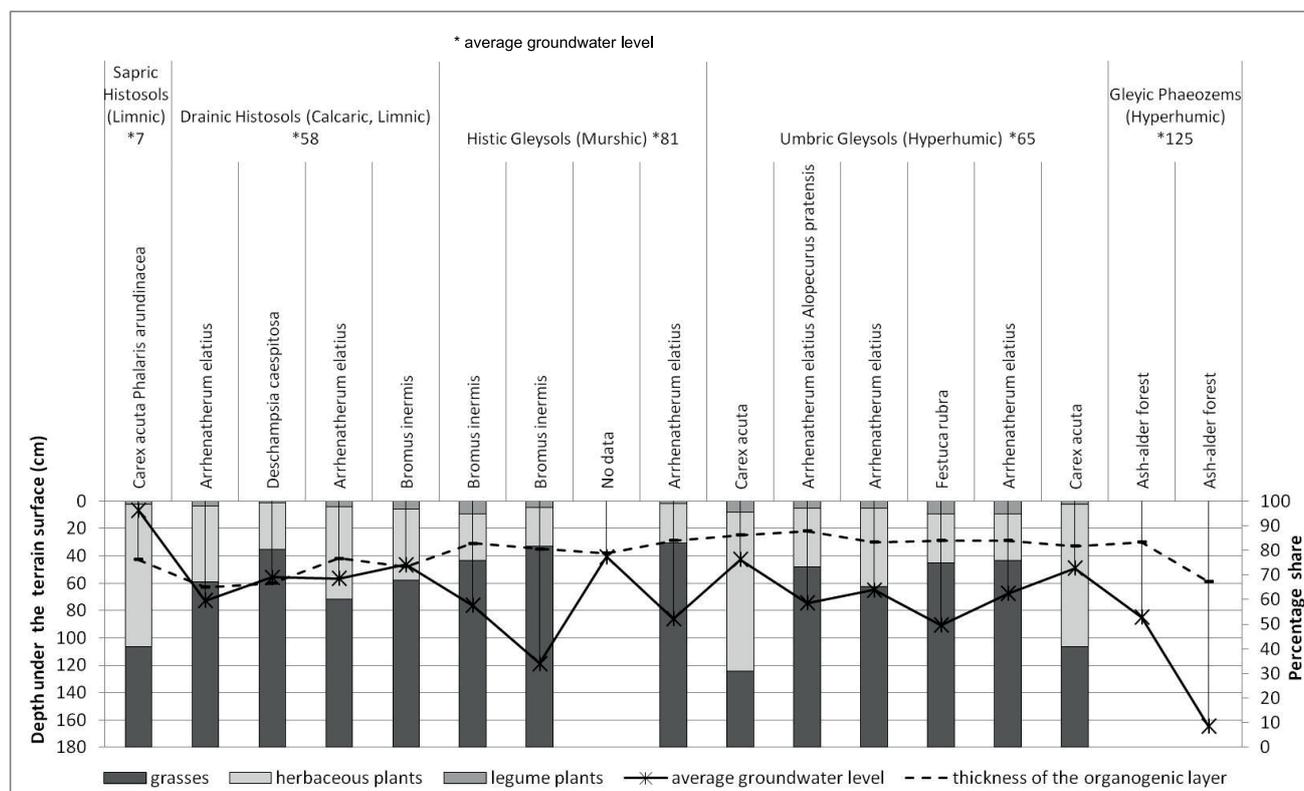


Fig. 4. Average (year) depth of water level in piezometers in areas of prevalence studied shallow organogenic soils on Holocene carbonate limnic deposits in NW Poland, thickness of organogenic layers and type of existing plant communities with percentage share of grasses, herbaceous and legume plants; source: own study

with wet conditions, were found in the area of Drainic Histosols (Calcaric, Limnic). However, the *Arrhenatherum elatius* and *Bromus inermis* species occurred in areas of deeper groundwater (approximately 70 cm under the terrain surface) on mucks and Umbric Gleysols (Hyperhumic). The plant community, where the dominant species was *Festuca rubra*, occurred in area of the deepest dehydrated muck soil (average 91 cm under the terrain surface). In terms of the sward composition, the largest share of herbs and weeds (>50%) was characterised by communities, where water occurred shallow (Kitczak *et al.*, 2014; Wallor and Zeitz, 2016), in the case of other communities, from 60 to almost 82% of grass dominated, and legume plants constituted from about 1–5%.

THE RELATIONSHIPS BETWEEN PROPERTIES OF SHALLOW CARBONATE SOILS, GROUNDWATER AND PLANT COVER

The degradation process of organogenic soils organic matter is the source of many mineral compounds in groundwater and surface water (Jaszczyński, 2008; Geurts *et al.*, 2010). The largest fluctuations in the groundwater level (standard deviation = 58.1) and the lowest average groundwater level (125 cm below the ground level) were found in the areas of Gleyic Phaeozems (Hyperhumic) (Fig. 4). However the most shallow groundwater level (7 cm below the ground level) and slightest fluctuations occurred in the case of Sapric Histosols (Limnic). In the case of Drainic Histosols (Calcaric, Limnic), Histic Gleysols (Murshic), Umbric Gleysols (Hyperhumic) average groundwater level during the research period ranged from 58 cm to 81 cm below the ground level and the water level fluctuations were quite similar (SD from 32.1 to 45.7). All groundwaters were alkaline (Tab. S2) and their pH increased with the lowering of the water level (Fig. 5). Alkaline reaction and high Ca content is characteristic of catchments, the structure of which enables decalcification of the structured formations (Kelts and Ksu, 1978). All the studied soils

occurred on limnic sediments containing about 80% of CaCO₃, the exception being the peat soil occurring on sediments containing nearly 70% of CaCO₃.

The highest content of Ca and Mg was found in shallow groundwater within the occurrence of Drainic Histosols (Calcaric, Limnic) with the most extensive organic level subject to a significant part of intensive mineralisation. This suggests that significant proportion of Ca and Mg load may come from the leaching processes of these elements from layers of organogenic muck soils, that are characterised by high sorption capacity and high Ca and Mg content (Piaścik and Gotkiewicz, 2004; Wallor and Zeitz, 2016). This theory is confirmed by PCA analysis showing a correlation between the sum of exchangeable cations, exchangeable Ca and Mg and the content of these elements in groundwater. A similar dependence is also exhibited by the content of P in plants, whereas the presence of P in water results mainly from organogenic layers (Geurts *et al.*, 2010; Ewing *et al.*, 2012), a very pronounced relationship can also be observed in the presence of Mg in plants. The Na content in the soil correlated with the content of Ca and Na in the sward.

Differentiation of the total nitrogen and potassium content in groundwater of individual study areas (1, 2, 3, 4 and 5) may result from diversified mineralogical composition and from the intensity of agricultural use (size and type of fertilisation, share of arable land in a separate part of the catchment and distance of these lands from research site) in areas near the research fields. Factorial analysis indicates the relationship of K content in groundwater, in plants (Tab. S2) and in the percentage of Ncf in soils, which is the main source of this element in the natural environment of post-bog soils on Holocene carbonate limnic deposits (Meller, 2006; Dobrowolski *et al.*, 2010; Okupny *et al.*, 2016). As Könönen *et al.* (2015) indicate, K in organic soils cannot compete for cation exchange sites with ions that have stronger electric charges (H, Ca, Mg) and can be easily leached or retained in the biological cycle by vegetation.

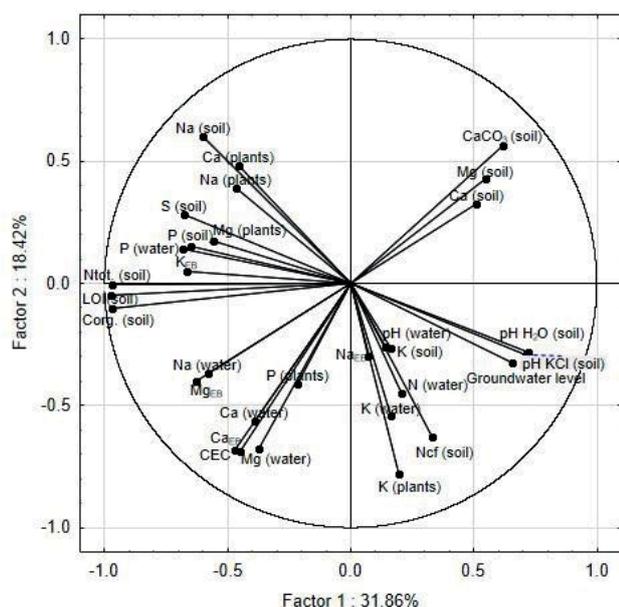


Fig. 5. Factor coordinates for components 1 and 2 for properties of shallow post-bog soils on Holocene carbonate limnic deposits (soil), water properties (water) and chemical properties of plant (plant); source: own study

CONCLUSIONS

Shallow organogenic soils developed on limnic carbonate sediments in their occurrence are subject to transformations, the main cause of which is dehydration caused by anthropogenic factors. Accumulation of organic matter gives way to the process of its mineralisation, and organic soils evolve towards mineral soils. Decomposition of surface layers of post-bog soils is associated with an increase in the proportion of CaCO₃ and mineral non-lime parts, which significantly affects the chemical and physical properties. In the organogenic layers of investigated post-bog soils, the content of elements associated with organic matter such as C, N and S decreases, and content of total Ca and Mg forms increases, the main source of which are the subsoil-building deposits. In the case of Fe, there are two sources, the first is the release of this element during mineralisation processes, the second is the Fe sorption with groundwater and the accumulation of groundwater surface in the form of oxides in the fluctuation zone.

The high sorption capacity of post-bog soils is related to the share of organic matter, with the exchangeable form of Ca accounting for 95% of the sum of all exchangeable cations. Statistical analysis proves that the greatest variation in the studied

soils results from the share of organic matter, and significant changes in chemical properties (content of CaCO₃, C, N, Ca, Mg, Ca_{EB}, and sum of exchangeable bases) are observed between organic and mineral layers. The change in the share of main components and structure in surface levels of post-soil soils causes their compaction, adversely affects porosity, impairs retention properties and may deepen the deficit of levels closest to the surface as a result of capillary leakage reduction.

The studied soils are associated with a wet environment in which mainly the level of humidity determines the composition of vegetation. In areas with different types of post-bog soils, the smallest share of grass in the sward was identified in the most humid areas where *Carex acuta* was predominant, while in deeper dehydrated areas mainly grasses from the following species: *Bromus inermis*, *Arrhenatherum elatius*, *Deschampsia caespitosa* and *Festuca rubra*. Evolving post-bog soils remain related to groundwater, affecting their composition by increasing the content of Ca and Mg. These metals in form of exchangeable cations are leached from surface levels. Post-bog soils have a specific place in ecosystems associated with inland lakes, and the shallow organogenic level makes them particularly vulnerable to degradation and complete transformation into mineral formations.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_Jarnuszewski.pdf.

REFERENCES

- Bothe, H. (2015) "The lime-silicate question," *Soil Biology & Biochemistry*, 89, pp. 172–183. Available at: <https://doi.org/10.1016/j.soilbio.2015.07.004>.
- Brouns, K., Verhoeven, J.T.A. and Hefting, M.M. (2014) "Short period of oxygenation releases latch on peat decomposition," *Science of the Total Environment*, 481, pp. 61–68. Available at: <https://doi.org/10.1016/j.scitotenv.2014.02.030>.
- Cabezas, A. et al. (2012) "Effects of degree of peat decomposition, loading rate and temperature on dissolved nitrogen turnover in rewetted fens," *Soil Biology & Biochemistry*, 48, pp. 182–191. Available at: <https://doi.org/10.1016/j.soilbio.2012.01.027>.
- Chimner, R.A. and Cooper, D.A. (2003) "Influence of water table levels on CO₂ emissions in a Colorado subalpine fen: an in situ microcosm study," *Soil Biology & Biochemistry*, 35(3), pp. 345–351. Available at: [https://doi.org/10.1016/s0038-0717\(02\)00284-5](https://doi.org/10.1016/s0038-0717(02)00284-5).
- Choiński, A. (2013) *Katalog jezior Polski [Catalog of Polish lakes]*. Poznań: Wyd. Nauk. UAM.
- Choiński, A., Ptak, M. and Strzelczak, A. (2012) "Examples of lake disappearance as an effect of reclamation works in Poland," *Limnological Review*, 12(4), pp. 161–167. Available at: <https://doi.org/10.2478/v10194-012-0056-2>.
- Collins, M.E. and Kuehl, R.J. (2001) "Organic matter accumulation and organic soils," in J.L. Richardson and M.J. Vepraskas (eds.) *Wetland soils: Genesis, hydrology, landscapes and classification*. Boca Raton, Florida: Lewis Publishers, pp. 137–162.
- Craft, C.B. (2001) "Biology of wetland soils," in J.L. Richardson and M.J. Vepraskas (eds.) *Wetland soils: Genesis, hydrology, landscapes and classification*. Boca Raton Florida: Lewis Publishers, pp. 107–135.
- Dawson, Q. et al. (2010) "Subsidence and degradation of agricultural peatlands in the Fenlands of Norfolk, UK," *Geoderma*, 154(3–4), pp. 181–187. Available at: <https://doi.org/10.1016/j.geoderma.2009.09.017>.
- Dobrowolski, R. et al. (2010) "Radiocarbon age and geochemistry of the infillings of small closed depressions from Western Polesie (Poland Se, Ukraine Nw)," *Geochronometria*, 36(1), pp. 39–46. Available at: <https://doi.org/10.2478/v10003-010-0010-8>.
- Ewing, J.M. et al. (2012) "Changes in wetland soil morphological and chemical properties after 15, 20, and 30 years of agricultural production," *Geoderma*, 179–180, pp. 73–80. Available at: <https://doi.org/10.1016/j.geoderma.2012.02.018>.
- Fell, H. et al. (2016) "Estimating vulnerability of agriculturally used peatlands in north-east Germany to carbon loss based on multi-temporal subsidence data analysis," *Catena*, 137, pp. 61–69. Available at: <https://doi.org/10.1016/j.catena.2015.08.010>.
- Filipiak, J. and Raczyński, M. (2000) *Jeziora zachodniopomorskie (zarys faktografii) [West Pomeranian Lakes (outline)]*. Szczecin: Wydawnictwo AR.
- FAO (2015) "World reference base for soil resources 2014: International soil classification systems for naming soils and creating legends for soil maps," *World Soil Resources Reports*, 106. Rome: Food and Agriculture Organization of the United Nations.
- Freytet, P. and Verrecchia, E.P. (2002) "Lacustrine and palustrine carbonate petrography: An overview," *Journal of Paleolimnology*, 27(2), pp. 221–237. Available at: <https://doi.org/10.1023/a:1014263722766>.
- Geurts, J. et al. (2010) "The interaction between decomposition, net N and P mineralization and their mobilization to the surface water in fens," *Water Research*, 44(11), pp. 3487–3495. Available at: <https://doi.org/10.1016/j.watres.2010.03.030>.
- PGI (2022) "Złoża kopalin [Mineral deposits]," in *System Gospodarki i Ochrony Bogactw Mineralnych "Midas" [System of Management and Protection of Mineral Resources "Midas"]* Available at: <http://geoportal.pgi.gov.pl/midas-web> (Accessed: November, 14, 2022).
- Gąsiorek, E. and Musiał, E. (2011) „Porównanie i klasyfikacja warunków opadowych na podstawie wskaźnika standaryzowanego opadu i wskaźnika względnego opadu [Comparison and classification of precipitation conditions based on standardized SPI and relative precipitation indices],” *Woda-Środowisko-Obszary Wiejskie*, 11(4), pp. 107–119.
- Gierlowski-Kordesch, E. (2010) "Chapter 1. Lacustrine carbonates," in *Developments in sedimentology*. Elsevier BV, pp. 1–101. Available at: [https://doi.org/10.1016/s0070-4571\(09\)06101-9](https://doi.org/10.1016/s0070-4571(09)06101-9).
- Glatzel, S., Lemke, S. and Gerold, G. (2006) "Short-term effects of an exceptionally hot and dry summer on decomposition of surface peat in a restored temperate bog," *European Journal of Soil Biology*, 42(4), pp. 219–229. Available at: <https://doi.org/10.1016/j.ejsobi.2006.03.003>.
- Gnatowski, T. et al. (2010) "Hydraulic properties of fen peat soils in Poland," *Geoderma*, 154(3–4), pp. 188–195. Available at: <https://doi.org/10.1016/j.geoderma.2009.02.021>.
- GUGiK (2022) *Digital Elevation Model (DEM)*. Warszawa: Head Office of Geodesy and Cartography. Available at: <https://mapy.geoport.gov.pl/> (Accessed: November 20, 2022).
- Ilnicki, P. (2002) *Torfowiska i torf [Peatlands and peat]*. Poznań: Wydaw. Akademii Rolniczej w Poznaniu.
- IMGW-PIB (2023) *Dane meteorologiczne [Meteorological data]*. Warszawa: Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy. Available at: [© 2023. The Authors. Published by Polish Academy of Sciences \(PAN\) and Institute of Technology and Life Sciences – National Research Institute \(ITP – PIB\). This is an open access article under the CC BY-NC-ND license \(<https://creativecommons.org/licenses/by-nc-nd/3.0/>\)](https://danepu-</p>
</div>
<div data-bbox=)

- blichzne.imgw.pl/data/dane_pomiarowo_obserwacyjne/ (Accessed: March 2, 2023).
- Jarnuszewski, G. (2015) "Chemical properties of organic soils developed from lacustrine chalk near the lakes Strzeszowskie, Sitno, and Sierakowo (Western Pomerania, north Poland)," *Roczniki Gleboznawcze*, 66(4), pp. 168–179. Available at: <https://doi.org/10.1515/ssa-2015-0034>.
- Jarnuszewski, G. (2016) "Characterization of some physical and chemical properties of post-bog soils developed from limnic deposits in vicinity of lake Dubie (Western Pomerania, NW Poland)," *Roczniki Gleboznawcze*, 67(1), pp. 24–31. Available at: <https://doi.org/10.1515/ssa-2016-0004>.
- Jaszczyński, J. (2008) "Groundwater quality against a background of human activities and impact of peatland area," *Agronomy Research*, 6, pp. 121–129.
- Kabała, C. et al. (2019) "Polish Soil Classification, 6th edition – principles, classification scheme and correlations," *Roczniki Gleboznawcze*, 70(2), pp. 71–97. Available at: <https://doi.org/10.2478/ssa-2019-0009>.
- Kaczorowska, Z. (1962) "Opady w Polsce w przekroju wieloletnim [*Precipitation in Poland in long-period averages*]," *Prace Geograficzne*, 33. Warszawa: IGiPZ PAN, Wydaw. Geologiczne.
- Kaiser, K. et al. (2012) "Late Quaternary evolution of rivers, lakes and peatlands in northeast Germany reflecting past climatic and human impact – An overview," *Eiszeitalter und Gegenwart*, 61(2), pp. 103–132. Available at: <https://doi.org/10.3285/eg.61.2.01>.
- Kechavarzi, C., Dawson, Q. and Leeds-Harrison, P.B. (2010) "Physical properties of low-lying agricultural peat soils in England," *Geoderma*, 154(3–4), pp. 196–202. Available at: <https://doi.org/10.1016/j.geoderma.2009.08.018>.
- Kelts, K. and Hsü, K.J. (1978) "Freshwater carbonate sedimentation," in A. Lerman (ed.) *Lakes: Chemistry, geology, physics*. New York, NY: Springer, pp. 295–323. Available at: https://doi.org/10.1007/978-1-4757-1152-3_9.
- Kitczak, T. et al. (2014) "Wpływ warunków siedliskowych na skład florystyczny, wartość użytkową i walory przyrodnicze użytków zielonych położonych nad jeziorem Miedwie [Effect of habitat for floristic composition, value in use natural values and green land located on Lake Miedwie]," *Inżynieria Ekologiczna*, 38, pp. 60–69. Available at: <https://doi.org/10.12912/2081139X.34>.
- Koźmiński, C., Michalska, B. and Czarnecka, M. (2007) *Klimat województwa zachodniopomorskiego [The climate of the West Pomeranian Voivodeship]*. Szczecin: Akademia Rolnicza, Uniwersytet Szczeciński.
- Könönen, M. et al. (2015) "Physical and chemical properties of tropical peat under stabilised land uses," *Mires and Peat*, 16, pp. 1–13.
- Łachacz, A., Nitkiewicz, M. and Pisarek, W. (2009), "Soil conditions and vegetation on gyttia lands in the Masurian Lakeland," *Contemporary Problems of Management and Environmental Protection*, 2, pp. 61–94.
- Marcinek, J. and Sychalski, M. (1998) "Degradacja gleb organicznych doliny Obry po ich odwodnieniu i wieloletnim rolniczym użytkowaniu [Degradation of organic soils in Obra river valley after their drainage and many year agricultural use]," *Zeszyty Problemowe Postępów Nauk Rolniczych*, 460, pp. 219–236.
- McCarter, C.P.R. et al. (2020) "Pore-scale controls on hydrological and geochemical processes in peat: Implications on interacting processes," *Earth-Science Reviews*, 207, 103227. Available at: <https://doi.org/10.1016/j.earscirev.2020.103227>.
- Meller, E. (2006) "Płytkie gleby organogeniczno-węglanowe na kredzie jeziornej i ich przeobrażenia w wyniku uprawy [Shallow organogenic-calcareous soils on lacustrine chalk and their transformation resulted from cultivation]," *AR w Szczecinie. Rozprawy*, 233.
- Offermanns, L. et al. (2023) "High greenhouse gas emissions after grassland renewal on bog peat soil," *Agricultural and Forest Meteorology*, 331, 109309. Available at: <https://doi.org/10.1016/j.agrformet.2023.109309>.
- Okruszko, H. (1988) "Zasady podziału gleb hydrogenicznych na rodzaje oraz łączenia rodzajów w kompleksy [*Taxonomy of hydrogenic soils and joining them into soils complex*]," *Roczniki Gleboznawcze*, 39(1), pp. 127–152.
- Okupny, D. et al. (2016) "Factors influencing temporal changes in chemical composition of biogenic deposits in the middle Tążyńska River Valley (Kuyavian Lakeland, central Poland)," *Geologos*, 22(2), pp. 121–136. Available at: <https://doi.org/10.1515/logos-2016-0013>.
- Oleszczuk, R. and Truba, M. (2013) "The analysis of some physical properties of drained peat-moors soil layers," *Annals of Warsaw University of Life Sciences, Land Reclamation*, 45(1), pp. 41–48. Available at: <https://doi.org/10.2478/ssgw-2013-0004>.
- Orzechowski, M., Smólczyński, S. and Sowiński, P. (2004) "Przekształcenia antropogeniczne gleb obniżen śródmorenowych Pojezierza Mazurskiego [Anthropogenic transformations of the mid-moraine depression soils in the Mazurian Lakeland]," *Roczniki Gleboznawcze*, 55(2), pp. 311–320.
- Piaścik, H. and Gotkiewicz, J. (2004) "Przeobrażenia odwodnionych gleb torfowych jako przyczyna ich degradacji [Transformation of dewatered peat soils as the cause of their degradation]," *Roczniki Gleboznawcze*, 55(2), pp. 331–338.
- PN-ISO 11466:2002. *Jakość gleby. Ekstrakcja pierwiastków śladowych rozpuszczalnych w wodzie królewskiej [Soil quality. Extraction of aqua regia soluble trace elements]*. Warszawa: Polski Komitet Normalizacyjny.
- PN-R-04014: 1991. 1991. *Analiza chemiczno-rolnicza roślin. Metody mineralizacji materiału roślinnego do oznaczania makro- i mikroelementów [Chemical and agricultural analysis of plants. Methods of mineralization of plant material for the determination of macro- and microelements]*. Warszawa: Polski Komitet Normalizacyjny.
- Prończuk, J. (1962) "Typologiczne zasady różnicowania trwałych użytków zielonych na przykładzie wydzielonych typów florystycznych w dolinach rzek niżu [Typological principles of diversification of permanent grassland on the example of specific floristic types in low river valleys]," in *Zastosowanie metody fitosocjologicznej i typologicznej do badań i ekspertyz łąkarskich [Application of phytosociological and typological methods for meadow studies and expert opinions]*, *Biblioteczka Wiadomości IMUZ*, 5, pp. 65–189.
- PTG (2019) *Systematyka gleb Polski [Polish soil classification]*. Wrocław–Warszawa: Wydawnictwo Uniwersytetu Przyrodniczego we Wrocławiu, Polskie Towarzystwo Gleboznawcze.
- Säurich, A. et al. (2019) "Drained organic soils under agriculture – The more degraded the soil the higher the specific basal respiration," *Geoderma*, 355, 113911. Available at: <https://doi.org/10.1016/j.geoderma.2019.113911>.
- Schnurrenberger, D., Russell, J.A. and Kelts, K. (2003) "Classification of lacustrine sediments based on sedimentary components. *Journal of Paleolimnology*, 29(2), pp. 141–154. Available at: <https://doi.org/10.1023/a:1023270324800>.
- StatSoft (2014) STATISTICA (data analysis software system), version 12.
- Verry, E.S. et al. (2011) "Physical properties of organic soils," in R.K. Kolka et al. (eds.) *Peatland biogeochemistry and watershed*

- hydrology at the Marcell Experimental Forest*. Boca Raton, FL: CRC Press, pp. 135–176.
- Wallor, E. and Zeitz, J. (2016) “How properties of differently cultivated fen soils affect grassland productivity – A broad investigation of environmental interactions in Northeast Germany,” *Catena*, 147, pp. 288–299. Available at: <https://doi.org/10.1016/j.catena.2016.07.024>.
- Wolejko, L., Herbichowa, M. and Potocka, J. (2005) “Typological differentiation and status of Natura 2000 mire habitats in Poland,” *Stappia*, 85, pp. 175–219.
- Yli-Halla, M. *et al.* (2022) “Thickness of peat influences the leaching of substances and greenhouse gas emissions from a cultivated organic soil,” *Science of the Total Environment*, 806, 150499. Available at: <https://doi.org/10.1016/j.scitotenv.2021.150499>.