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Organic soils and other soils rich in organic matter in the vicinity of the Łuknajno lake, Masurian Lakes Biosphere Reserve, NE Poland

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Abstract

The study covers the immediate surroundings of the Łuknajno lake. The soil cover here is largely affected by the water regime, i.e. ground water level. Eleven soil profiles were described, and the following analyses were carried out: soil texture (in mineral soil materials), $CaCO_3$ content, soil reaction, organic carbon and total nitrogen contents, specific and bulk density, total porosity, and organic carbon stock. According to the Polish Soil Classification (2019), six soil profiles were classified within the order of organic soils (4 profiles as peat soils, one as murshic soil and one as gyttja soil). Mineral soil profiles were classified as: mineral-peaty gleysol, gleyic chernozemic colluvial soil, humic regosol, typical semimurshic soil and typical postmurshic soil. According to the WRB classification (2022), 5 profiles were classified as Histosols (Drainic Sapric Histosols, Murshic Fibric Histosols, Murshic Sapric Histosols, Rheic Histosols). The neighbouring soils were classified as: Calcaric Histic Gleysols, Calcaric Regosols, Haplic Umbrisols, Gleyic Arenosols, Mollic Gleysols, Eutric Arenosols. The properties of studied soils are related to the high content of calcium carbonate which was leached from the soils of the catchment area and had accumulated in the basin of the Łuknajno lake in the form of thick layers of calcareous gyttja. The characteristic feature of studied soils is high organic carbon stock. For organic soils this stock was within the range of 74.4–111.9 kg C_{org} m^{-2} (to 150 cm down the soil profile). The neighbouring soils also have significant organic carbon stock (15.8–28.6 kg m^{-2}), which is recognizably higher than the stock in mineral sandy soils. Therefore, in estimations of organic carbon stock these soils should be taken into account although they cover small and scattered areas.

1. Introduction

Organic soils perform a number of important functions in the environment, which derive from the high content of organic matter and the occupation of the lowest places in the landscape, where water accumulates. These soils constitute a significant organic carbon stock and participate in the circulation of C in the environment (Okruszko, 1993; Ilnicki, 2002; Kalisz and Łachacz, 2023; Tuohy et al., 2023). The accumulation of organic carbon in the soil (and sequestration of CO_2 from vegetation building peat deposits) depends on the water conditions of the habitat. When drained, these soils emit CO_2 into the atmosphere and release biogenic compounds to surface and ground waters (Okruszko, 1993; Leifeld et al., 2011; Oleszczuk et al., 2022; Łachacz et al., 2023). Beside organic soils, the soils accompanying them in the landscape play a significant role in the circulation of carbon and nutrients. These are peatland's neighbouring soils, rich in organic matter, which developed in at least periodically in semihydrogenic conditions (gleyic conditions from groundwater). Gleyic soils after drainage are transformed into black earths when the underlying mineral material is finer or into semimurshic and postmurshic soils when this material is sandy (Łachacz, 2001; Łabaz and Kabała, 2016; Łachacz et al., 2023).

Beside organic soils, peatland neighbouring soils may have significantly high organic carbon stock which is treated as an important indicator of the state of the environment (Lorenz et al., 2019; Vittori Antisari et al., 2023).

In the young-glacial landscape, the origin of peatlands is usually associated with terrestralization of lakes and peatlands development. Hence, in the lower parts of peat soil profiles, limnic materials, like gyttja, with a varied content of organic matter and calcium carbonate usually occur (Uggla, 1964, 1976; Prusinkiewicz and Noryśkiewicz, 1975; Tobolski, 2000; Gąsiorowski, 2001; Ilnicki, 2002; Jarnuszewski and Meller, 2018, 2019; Bartmiński et al., 2022; Jarnuszewski et al., 2023). There are also specific wetlands, termed gyttjalands, in which limnic sediments occur on the surface. Bellamy (1962) described this phenomenon in the following words: “it is interesting to note that some of the bays of even the Lake Śniardwy are almost filled by a white “gyttja” like deposit over which the lake fringe vegetation is growing.” Development of gyttjalands is a consequence of sudden draining of the lake as a result of hydrotechnical works, which was common in the Masurian Lake District in the second half of the 19th century (Srokowski, 1930; Lemkowska and Sowiński, 2018). Therefore, beside numerous lakes, peatlands and gyttjalands are present in the landscape. In addition to human activity, the evolution of lakes was also influenced by climatic changes (Dąbrowski, 2002; Novik et al., 2010; Kruczkowska, 2024).

In order to protect the unique features of the young glacial landscape and biodiversity, the most valuable areas of the Masurian Lake District have been covered by various forms of nature protection. In the nature protection system of this region, an important role is played by the Masurian Lakes Biosphere Reserve, which includes the Łuknajno lake (previously protected as a Biosphere Reserve), as well as a significant part of the Masurian Landscape Park. A Chara-type Łuknajno lake is an example of the last stage of terrestralization (disappearance) of an eutrophic lake. The high content of $CaCO_3$ in the catchment soils, their high permeability and significant land denivelations caused the leaching of the mineral compounds and their deposition in the lake's basin. On the calcareous deposits in this lake, the so-called chara meadows (*Chara*) have developed, which currently participate in the processes of biological precipitation and accumulation of calcium carbonate (Królikowska, 1997; Kufel and Kufel, 1997).

Apart from the work of Polakowski et al. (1973), in which 7 soil profiles were briefly described, the soil cover of the Łuknajno lake catchment area has not been the subject of scientific research so far. The soils of this area are a good example of sediment accumulation in the lake basin, their transformation into subaerial soils and further evolution in the varying water-air relations. Due to the fact that the condition of the lake depends, to a large extent, on the processes occurring in its catchment area, the study was carried out in the immediate surroundings of the lake in order to document the state of the natural environment of this valuable protected area.

2. Study area

The study covered the immediate surroundings of the Łuknajno lake (53°49’ N, 21°38’ E) located in the southwestern part of the Great Masurian Lakes District, approx. 6 km east of Mikołajki. The climate of this part of Poland has been classified as temperate oceanic climate (Cfb) according to the Köppen-Geiger climate classification (Kottek et al., 2006). Average annual temperaturę is 8.3°C, and average annual precipitation is 718 mm. The Great Masurian Lakes District is a mesoregion within the Masurian Lakeland macroregion (Solon et al., 2018). A characteristic feature of this region is the large area occupied by lakes, the connection of which by canals into one system resulted in the equalization of the water table at 115.7 m above sea level (Lisicki, 2001). The first canals were constructed in 1764–1765, connecting the lakes Mamry, Niegocin and Śniardwy. Further drainage works in the 19th century caused a significant lowering of the water table in other, neighbouring lakes and in the wetlands adjacent to them. The Łuknajno lake is located directly north of the largest lake in Poland, the Śniardwy lake, with which it was connected by a shallow isthmus, and currently, after land reclamation, it is connected by a short canal. The lowering of the water table by 2.5 m in 1827 was crucial for the evolution of the Łuknajno lake, because it accelerated the process of its disappearance (terrestralization) (Olszewski and Paschalski, 1959).

The Łuknajno lake basin was formed as a result of the melting of a block of dead ice at the beginning of the Holocene, probably at the turn of the Alleröd and the Younger Dryas. In the past, probably already in the Bölling period, the Łuknajno lake was part of a shallow and extensive reservoir, the so-called Pra-Śniardwy, which area is estimated to be at least twice as large as the present one (Lisicki, 2001). The final shape of the terrain is a derivative of the processes occurring in the Holocene, which contributed to the formation of biogenic and lacustrine plains. Lake terraces and the accompanying coastal embankments in the eastern shore also come from this period. The main sediments building this area include organic sediments, in the form of low moor peats (fens), currently in some places under the mursh-forming process. Limnic sediments in the form of organic and calcareous gyttja, which often lie close to the surface, are also common.

In morphogenetic terms, the Łuknajno lake catchment area lies in the marginal zone of the maximum extent of the Pomeranian phase of the Vistulian glaciation. The area is characterized by a large variety of geomorphological forms at rather small area (Lisicki, 2001). The diversity of forms and their specific distribution entails the diversity of sediments which are parent materials for soils.

The Łuknajno lake covers an area of 623 ha (surface water area) and accumulates 4,351 thousand m^3 of water, with a maximum depth of 3 m and an average depth of 0.6 m (Olszewski and Paschalski, 1959; Królikowska, 1997). The immediate lake watershed of area of 48.4 km^2, is composed of arable lands (55%), meadows and pastures (26%) as well as forests (19%). Sandy, permeable soils dominate in the watershed (Kufel and Kufel, 1997). The basin of the lake is filled with calcareous gyttja in approximately 90% of its volume, and its thickness reaches several meters (>10 m) (Więckowski, 1966; Lisicki, 2001).

In lake waters, on the calcareous gyttjas, chara meadows (*Charetum aculeolatae, Ch. contrariae, Ch. asperae, Ch. tomentosae*) have developed. Submerged vegetation occupies about 50% of the bottom. In some places, communities of vascular plants with floating leaves (*Potametum lucentis*) have developed. The lake shores are overgrown with rush communities (*Phragmitetum australis, Acoretum calami, Caricetum appropinquatae, C. elatae*), and in places with willow thickets (*Salicetum pentandro-cinereae* and plant community with *Salix aurita*) (Polakowski et al., 1973). On the northern and western sides, the current lake is adjoined by fens covered mainly with sedges, and in some places also with willow thickets. Further from the lake, these peatlands are used as meadows. The peatlands to the north-west of the lake form a vast complex reaching the Tałtowisko lake (the so-called Tałckie Bagno). In the southern part, near the Śniardwy lake, forests prevail, mainly alder forests and lakeside forests (*Salici-Franguletum, Ribeso nigri-Alnetum*). The eastern shore of the Łuknajno lake is higher, with mineral and mineral-organic soils, formerly in some places agriculturally used.

The Łuknajno lake has been protected as an ornithological reserve since 1937. After the World War II, in 1947, it was under protection as an ornithological nature reserve in order to protect the habitats of the mute swan (*Cygnus alor*), which forms one of the largest colonies in Europe there. In addition to this species, there are numerous other species of wetland birds, including rare and endangered ones. The above facts have gained international recognition, as evidenced by the inclusion of this reserve on the UNESCO list of biosphere reserves in 1977, and on the list under the Ramsar Convention in 1978. The Masurian Lakes Biosphere Reserve was created in 2017 by way of renomination of the previous Łuknajno Lake Biosphere Reserve. After enlargement, the reserve covers 58,693.71 ha, including 6,786.90 ha of the core area. Currently, beside the Łuknajno lake, it covers a significant part of the Masurian Landscape Park.

3. Materials and methods

The studied soils were described in field, the soil color was determined in moist samples, and then in laboratory, by applying Munsell color charts to air-dry soil samples (Munsell Color Company, 1994). Degree of peat decomposition was estimated by the field method proposed by von Post (PSC, 2019). The soil samples were collected and air-dried at room temperature, visible roots and other living plant remnants were removed manually. The soil was gently crushed with a rolling pin, and sieved through a 2 mm mesh sieve. The soil texture (in mineral soil materials) was determined by the sieve method and the hydrometer (the Bouyoucos areometric, modified by Cassagrande and Prószyński) method, and the results were presented as texture class according to USDA classification, adopted by WRB (IUSS Working Group WRB 2022). Sedimentological indices based on the Folk and Ward classification (Prusinkiewicz and Proszek, 1990; Sowiński et al., 2023) were calculated using the SIEWCA software (Siewca, 2010):

– mean grain diameter (Mz), for particle size fractions from 2.0 mm to <0.002 mm;
– standard deviation (δ1), based on the degree of soil material sorting;
– skewness (Sk1), which defines the difference between deviations from the mean;
– kurtosis (Kg), as a relative measure of the concentration and flattening of the distribution, determines the distribution and concentration of the value of a variable around the mean.

Additionally, undisturbed core samples were collected into 100 cm^3 steel cylinders to determine bulk density (BD), by drying at a temperature of 105°C. Specific density (SD) was measured by a pycnometer method. Total porosity (TP) was calculated using an equation:

$$TP = (SD - BD)/SD \times 100\ [\%, vol.] \quad (1)$$

The following soil properties were determined in air-dried soil samples: $CaCO_3$ equivalent by the Scheibler's volumetric method, loss-on-ignition (LOI) after dry ashing for 6 hours at a temperature of 550°C in a muffle furnace, which approximates the amount of soil organic matter (SOM), total organic carbon ($C_{org.}$) and total nitrogen ($N_{tot.}$) contents with a Vario Max Cube CN elemental analyzer, soil reaction (pH) potentiometrically in distilled water and in potassium chloride (1 mol KCl dm^{-3}; fresh soil-to-solution ratio of 1:2.5 v/v) (Sapek and Sapek, 1992; van Reeuwijk, 2002). For total organic carbon ($C_{org.}$) measurements, the soil samples were acidified with hydrochloric acid (1:1 v/v) in order to remove inorganic carbon, and then C (organic carbon) was determined using an analyser (at 900°C; with thermal conductivity detector). The results were converted to absolute dry matter (drying at 105°C) and presented as an arithmetic mean from two parallel determinations.

Soil organic carbon stock (SOCstock) was calculated for each soil layer with determined $C_{org.}$ content and bulk density using an equation:

$$SOCstock = h \times BD \times C_{org.} \times (1 - SP)/100 \quad (2)$$

where:
SOCstock – soil organic carbon stock [kg m^{-2}]
h – thickness of soil layer [cm]
BD – dry bulk density [g cm^{-3}]
$C_{org.}$ – organic carbon content [g kg^{-1}] of the fine earth of soil
SP – volumetric fraction of skeletal particles (> 2 mm)

In mineral horizons, the content of skeletal particles was taken under consideration, as the presence of these particles reduces the organic carbon stock (Fenton et al., 2024).

4. Results and discussion

4.1. Morphology of soils and soil classification

In the vicinity of the Łuknajno lake, soils with different organic matter content have developed, depending on their location in relation to the current shore of the lake. The soil profiles were grouped in three locations near the shore of the Łuknajno lake (Fig. 1). Profiles no. 1–4 are located southwest of the lake shore. Profile no. 4 is located closest to the lake shore (ca. 200 m). These profiles are located at a similar height (116.3–116.5 m a.s.l.), and thus slightly above the current average water level in the lake (115.7 m a.s.l.) (Table 1). Profiles no. 5–7 are located west of the lake shore near a small elevation (a mineral island surrounded by a peatland). The highest is profile no. 7 (119.2 m a.s.l.), located at the edge of this elevation. The closest to the lake shore (approx. 70 m) is profile no. 6 (height 116.2 m a.s.l.), with the highest groundwater level of the soils studied. Profiles no. 8–11 are located on the eastern shore of the lake. The shore is higher here, formed by sands remodelled by wave activity. Profile no. 10 is located closest to the shore (20 m) at

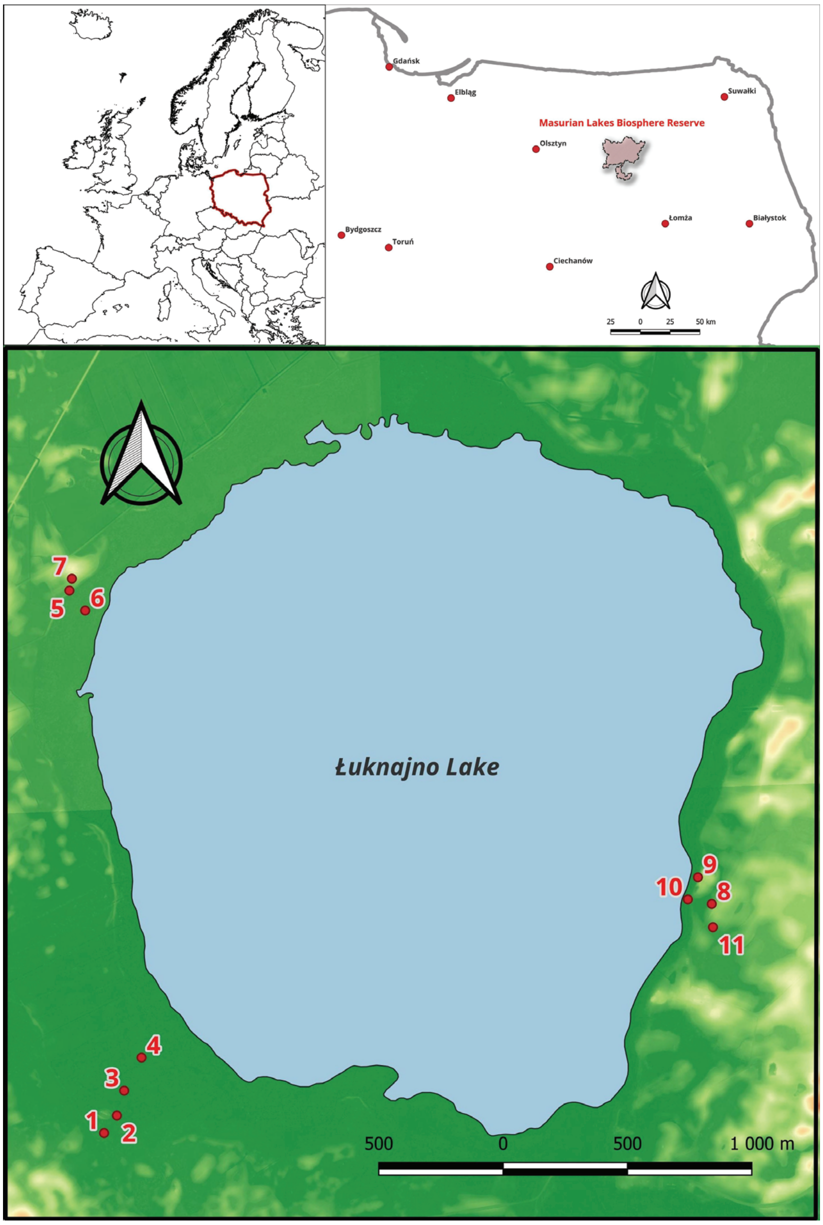

Fig. 1. Location of the studied soil profiles in the vicinity of the Łuknajno Lake in the Masurian Lakes Biosphere Reserve

Table 1
Location of soil profiles studied

Soil profile number	Elevation (m a.s.l.)	Land cover	Coordinates (WGS 84)	
			latitude	longitude
1	116.5	toll-herb vegetation with *Filipendula ulmaria*	53.8008	21.6065
2	116.4	abandoned meadow	53.8014	21.6073
3	116.3	*Phragmites australis* rushes	53.8023	21.6078
4	116.4	*Phragmites australis* rushes	53.8035	21.6089
5	117.1	toll-herb vegetation	53.8197	21.6065
6	116.2	*Phragmites australis* rushes	53.8204	21.6056
7	119.2	abandoned arable field	53.8209	21.6058
8	118.2	alder forest (*Ribeso nigri-Alnetum*)	53.8083	21.6441
9	117.1	willow thickets (*Salicetum pentandro-cinereae*)	53.8074	21.6441
10	116.4	willow thickets (*Salicetum pentandro-cinereae*)	53.8092	21.6433
11	117.7	toll-herb vegetation with *Urtica dioica*	53.8085	21.6426

an altitude of 116.4 m a.s.l.). Profile no. 9 (height 117.1 m a.s.l.) is located at the foot of a small elevation, hence the effect of colluvial processes is visible in it.

The distribution of soils is related to water relations, especially to the groundwater level. Six of the studied soils were classified as organic soils (SGP 2019; Kabała et al., 2019). Among the soils belonging to the organic order, four profiles (no. 1, 2, 3, 5) were classified as peat soils, one profile (no. 4) was classified as mursh soil and one profile (no. 6) was classified as gyttja soil (Table 2, Fig. 2). All organic soils (except profile no. 4) have a varied thickness of mursh in the topsoil, from 13 cm to 27 cm (but less than 30 cm, which is the criterion distinguishing peat soils from mursh ones). The occurrence of mursh in the topsoil is related to the artificial lowering of the water level in the Łuknajno lake in the 19th century, which caused a lowering of the groundwater level in the surrounding peatlands. The studied organic soils contain peats typical for post-lake fens, mainly low sedge-moss peat, alder-rush peat, alder swamp forest peat, and in profile no. 1 also sedge peat.

As a result of the mursh formation, the bulk density in the mursh horizons increases (0.27–0.33 g cm^{-3}) and the total porosity decreases (80.0–84.9%) in relation to the peats beneath (BD: 0.13–0.19 g cm^{-3}; TP: 88.8–91.8%). The physical properties of studied organic soils are typical for the genetic types of peat they represent and are similar to those reported in the literature (Piaścik and Łachacz, 1997, 2001).

In the studied soils, peats are underlain by limnic materials in the form of detrital-calcareous gyttja, lacustrine marl, proper lacustrine marl, and in deeper layers also by clay-calcareous gyttja. It should be noted that these limnic materials contain large amounts of $CaCO_3$. On the other hand, profile No. 6 is composed entirely of limnic materials: coarse detrital gyttja on the top, fine detrital gyttja beneath it, and at a depth of 73–98 cm detrital-calcareous gyttja underlain by clay-calcareous gyttja.

On the eastern shore of the Łuknajno lake, there are soils that do not belong to the organic order, but due to water conditions (periodically high groundwater level), they contain

Table 2
General description of the soil profiles

Depth [cm]	Soil horizon PSC (2019)	Soil horizon WRB (2022)	Soil material/ texture class*	Degree of decomposition**	LOI	$CaCO_3$	pH		Munsell colour	
					[%]		H_2O	KCl	moist	dry
Profile 1, PSC (2019): gleba torfowa saprowa murszowa / sapric murshic peat soil WRB (2022): Drainic Sapric Histosol (Eutric)										
0–19	Md	Had	mursh	–	71.3	0.0	6.4	6.0	10YR2/1	10YR3/2.5
19–97	Oa1	Ha1	sedge peat	H8	91.9	0.0	6.2	5.5	10YR2/1	10YR3/2
97–150	Oa2	Ha2	low sedge-moss peat	H7	94.1	0.0	6.4	5.8	10YR2/1	10YR3/2
Profile 2, PSC (2019): gleba torfowa saprowa murszowa / sapric murshic peat soil WRB (2022): Drainic Sapric Histosol (Eutric)										
0–13	Md	Had	mursh	–	76.0	0.0	7.0	6.5	10YR2/1	10YR3/3
13–42	Oa1	Ha1	alder swamp forest peat	H9	78.0	0.0	6.7	6.3	10YR2/1	10YR2.5/1
42–91	Oa2	Ha2	alder-rush peat	H8	82.7	0.0	6.6	6.2	10YR2/1	10YR3/2
91–150	Lca	Cαλ	lacustrine marl	-	1.1	22.3	7.9	7.6	5Y7/1	5Y6/2
Profile 3, PSC (2019): gleba torfowa fibrowa murszowa (saprowa) / fibric murshic peat soil (sapric) WRB (2022): Rheic Murshic Fibric Histosol (Eutric, Hyperorganic)										
0–24	Md	Had	mursh	–	83.0	0.0	6.6	6.1	10YR2/1	10YR3/3
24–57	Oa	Ha	low sedge-moss peat	H7	89.5	0.0	6.7	5.9	10YR2/1	10YR3/2
57–92	Oi1	Hi1	low sedge-moss peat	H3	90.1	0.0	6.9	6.2	10YR2/1	10YR3/2
92–150	Oi2	Hi2	alder-rush peat	H3	93.6	0.0	6.9	6.2	10YR2/2	10YR3/2.5
150–171	Oe	He	alder-rush peat	H5	90.9	0.0	6.9	6.1	10YR3/2	10YR3.5/1
171–200	Lcca1	Hαλ	detrital-calcareous gyttja	–	63.3	32.2	8.3	8.2	2.5Y5/2	2.5Y4.5/1
200 +	Lcca2	Cαλ	clay-calcareous gyttja	–	24.8	48.7	8.4	8.3	2.5Y6/2	2.5Y4.5/2
Profile 4, PSC (2019): gleba murszowa gytiowa limnowęglanowa / gyttja murshic soil (limni calcareous) WRB (2022): Calcaric Histic Gleysol (Drainic, Limnic)										
0–33	Md	Had	mursh	–	83.0	0.0	6.8	6.4	10YR2/1	10YR3/2
33–39	Oa	Ha	low sedge-moss peat	H9	81.3	0.0	7.4	6.9	10YR2/1	10YR3/2
39–87	Lcca1	Cαλ1	proper lacustrine marl	–	10.5	43.8	8.2	8.1	5Y6/2	5Y7/1
87–150	Lcca2	Cαλ2	proper lacustrine marl	–	9.3	62.5	8.6	8.5	5Y5.5/2	5Y7/1.5

Table 2 – continue

Depth [cm]	Soil horizon PSC (2019)	Soil horizon WRB (2022)	Soil material/ texture class*	Degree of decompo-sition**	LOI	$CaCO_3$	pH		Munsell colour	
					[%]		H_2O	KCl	moist	dry
Profile 5, PSC (2019): gleba torfowa saprowa murszowa / sapric murshic peat soil WRB (2022): Murshic Sapric Histosol (Eutric)										
0–14	Md	Had1	mursh	–	76.8	0.0	6.9	6.5	10YR2/1	10YR3/2
14–27	M	Had2	mursh	–	74.5	0.0	6.8	6.5	10YR2/1	10YR3/2
27–63	Oa1	Ha1	alder-rush peat	H8	88.6	0.0	6.6	6.3	10YR2/1	10YR3/2
63–97	Oa2	Ha2	alder-rush peat	H8	87.4	0.0	6.3	5.8	10YR2/2	10YR3/2
97–150	Lcca	Cαλ	clay-calcareous gyttja	–	28.8	46.2	8.1	7.8	5Y4/1	5Y6/1
Profile 6, PSC (2019): gleba gytiowa limnowęglanowa / limni calcareous gyttja soil WRB (2022): Rheic Histosol (Eutric, Limnic)										
0–37	Lc1	Hλ1	coarse detrital gyttja	–	78.0	0.0	6.7	6.0	2.5Y2.5/1	2.5Y3/2
37–52	Lc2	Hλ2	fine detrital gyttja	–	44.2	0.0	6.8	6.2	2.5Y2.5/1	2.5Y3/1
52–73	Lc3	Hαλ	fine detrital gyttja	–	41.2	5.2	7.1	6.5	2.5Y4/2	2.5Y3/2
73–98	Lcca1	Cαλ1	detrital-calcareous gyttja	–	35.2	24.4	7.8	7.0	5Y4/1	5Y6/1
98–150	Lcca2	Cαλ2	clay-calcareous gyttja	–	20.2	48.5	8.2	7.4	5Y5/1	5Y7/1
Profile 7, PSC (2019): regosol próchniczny (węglanowy) / humic regosol (calcareous) WRB (2022): Calcaric Regosol (Anoarenic, Endoloamic, Drainic, Raptic, Mulmic)										
0–22	Aud	Ah	semimurshic	–	16.8	0.0	7.4	7.0	10YR2/1	10YR4/1.5
22–53	CAca	Cα1	loose sand	–	1.4	9.1	7.9	7.7	10YR4/2	10YR6/2
53–150	Cca	Cα2	sandy loam	–	1.3	12.5	8.1	7.5	10YR4.5/2	10YR6/2
Profile 8, PSC (2019): gleba murszowata typowa / typical semimurshic soil WRB (2022): Haplic Umbrisol (Pantoarenic, Drainic, Humic)										
4–0	Olf		forest litter	–	93.5	0.0	5.9	5.3	7.5YR2.5/2	7.5YR3/3.5
0–17	Au1	Ah1	semimurshic	–	13.6	0.0	6.1	5.6	10YR2/1	10YR3.5/1.5
17–39	Au2	Ah2	semimurshic	–	14.0	0.0	5.9	5.1	10YR2/1	10YR3.5/1
39–57	AC	AC	loose humose sand	–	2.5	0.0	7.4	7.1	10YR3/2	10YR5/2
57–150	C	C	loose sand	–	1.1	0.0	8.0	7.8	10YR3.5/3	10YR6/3
Profile 9, PSC (2019): gleba deluwialna czarnoziemna gruntowo-glejowa / gleyic chernoziemic colluvial soil WRB (2022): Eutric Gleyic Arenosol (Sombric)										
4–0	Olf		forest litter	–	92.1	0.0	6.0	5.3	7.5YR2.5/2	7.5YR3/4
0–26	Au	Ah	postmurshic	–	5.0	0.0	6.9	6.7	10YR3/2	10YR4.5/2
26–60	AC	ACr	loose humose sand	–	1.6	0.0	7.7	7.3	10YR4/2.5	10YR5/2
60–72	Ahb	Ahr	peaty-humose sand	–	15.1	0.2	7.7	7.5	2.5Y3/1	2.5Y4/1.5
72–150	Cgg	Cr	loose sand	–	1.9	1.1	7.9	7.8	2.5Y4/2	2.5Y6/2
Profile 10, PSC (2019): gleba gruntowo-glejowa torfiasta / mineral-peaty gleysol WRB (2022): Eutric Mollic Gleysol (Pantoarenic, Drainic)										
5–0	Olf		forest litter	–	93.4	0.0	6.9	5.9	10YR2/2	10YR3.5/2
0–28	Ah	Ah	peaty-humose sand	–	11.5	0.0	7.3	7.0	10YR2/1	10YR4/1
28–41	Cgg	Cr1	loose sand	–	0.8	0.0	7.6	7.3	2.5Y4.5/2.5	2.5Y5.5/1.5
41–150	G	Cr2	loose sand	–	0.7	0.0	7.6	7.4	5Y4.5/2	10YR6/1.5
Profile 11, PSC (2019): gleba murszasta typowa (głęboko próchniczna) / typical postmurshic soil (deep humic) WRB (2022): Eutric Arenosol (Humic)										
0–38	Ad	Ah1	loose humose sand	–	2.8	0.0	5.8	5.1	10YR3/1	10YR5/2
38–67	Ab	Ah2	postmurshic loose sand	–	3.7	0.0	6.7	6.0	10YR2.5/1	10YR5/1.5
67–81	ACb	AC	loose humose sand	–	1.9	0.0	6.8	6.1	10YR3/2	10YR4.5/2
81–150	C	C	loose sand	–	0.6	0.0	7.0	6.4	10YR5/3	10YR6/3

* – according to Polish Soil Classification (2019); ** – according to von Post (PSC, 2019); LOI – loss-on-ignitio

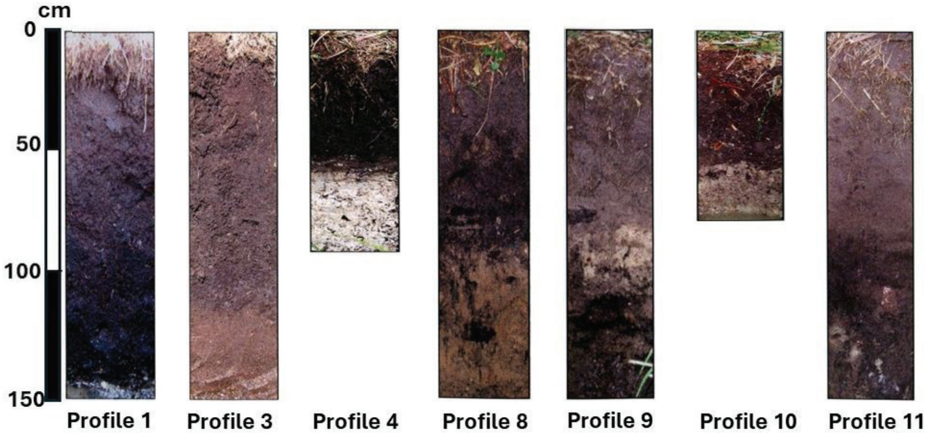

Fig. 2. Selected soil profiles studied (soil profile numbers as in Table 2)

significant amounts of SOM. They belong to different orders and types in SGP (2019). Profile no. 7, located on the edge of the hummock, represents humous (carbonate) regosol. In the surface horizon (0–22 cm), there is semimurshic soil material, which is gradually underlain by sand with 1.4% organic matter content. Soils no. 8, 9 and 11, formerly (until the 1980s) used for agricultural purposes, as arable land and meadow, are currently overgrown by shrubs and young forests as a result of spontaneous plant succession after discontinuation cultivation. Therefore, the topsoil is composed of a 4–5 cm epihumus layer (forest litter). Typical semimurshic soil (profile no. 8) has a semimurshic horizon (Au) of considerable thickness (39 cm. Below, a transitional horizon (AC) occurs, and at 57 cm sand lies. Profile no. 9 is classified as gleyic chernoziemic colluvial soil. Postmurshic soil material (0–26 cm) and humous sand (26–60 cm) beneath have colluvial origin, and cover the fossil horizon Ahb (60–72 cm) developed from peaty-humous sand, which is underlain by gleyic sand (Cgg horizon) at a depth of 72 cm. Markiewicz et al. (2017) suggested acceleration of water erosion in the vicinity of drained lakes and agricultural (plough) used catchment soils. The above study also documents the deep occurrence of horizons containing SOM in the vicinity of the disappeared lake. Profile no. 10 is a mineral-peaty gleysol, with Ah horizon (0–28 cm) developed from peaty-humous sand, and gleyed sand deeper. Profile no. 11 is a typical postmurshic soil (deep humic). Characteristic is the considerable thickness of horizons containing high amounts of SOM: Ad (0–38 cm) and Ab (38–67 cm), and the transitional horizon ACb (67–81 cm) containing still 1.9% of SOM.

In the soils of profiles no. 7, 8 and 11, low values of chroma (in the Munsell colour system) in dry soil and the resulting wide ratio of the value : chroma (in the range of 2.2–3.5) are typical. They indicate a low content of amorphous (coloured) iron compounds, which results from the fact that they were removed (washed out) from the topsoil before their drainage (Łachacz and Załuski, 2023). On this basis, it can be assumed that the accumulation of organic matter took place under the conditions of soil gleying. In other words, these soils did not form as a result of long-term intensive drainage of mursh soils, which due to the capillary rise of water rich in dissolved iron compounds usually contain higher amounts of iron (Łachacz et al., 2023).

4.2. Granulometric composition of mineral soils

The texture of studied mineral soils is sandy (Table 3). According to the USDA classification, it is sand (S), and only in profile no. 7, sand is underlain by sandy loam (SL) at a depth of 53–150 cm. The soils are characterized by a low (close to 0%) content of the clay fraction and a low content of silt fraction (0–8%). Only in profile no. 7, at the depth of 53–150 cm, the content of silt fraction amounted to 40%. The content of the sand fraction in the studied soils is in the range of 91–100%. The content of the skeletal fraction (gravel) is varied (0–10%). Sedimentological indices indicate the dominance of the sand fraction (Mz – 0.23–0.41 mm) and good sorting of the material. An exception is mentioned above texturally contrasted profile no. 7, where at a depth of 53 cm there is a sudden change in grain size, which is also documented by sedimentological indices, especially Mz and $\delta 1$ (Fig. 3; marked blue).

Low values of standard deviation of 1.23 found in profile no. 9 (72–150 cm), and of 1.39–1.41 in profile no. 10 (28–150 cm) indicate very good sorting of soil material representing sandy lake sediments (Fig. 3; marked red). Sedimentological features may therefore indicate processing of previously deposited sandy material as a result of waves activity of the Łuknajno lake. The current mineral soils (profiles no. 8–11) were therefore developed on lake terraces, the shores of the former lake. Cyclic washing of sandy shore sediments by the waters of a large lake deprived them of the finest clay-silt fraction, which was accumulated in the bottom sediments, where clay-calcareous gyttja occurs. This process took place mainly in the first half of the Holocene, before the development of vegetation in the catchment area of the Łuknajno lake. It is assumed that the accumulation of lacustrine clay usually occurred in the early stages of lake evolution (Uggla, 1968; Jarnuszewski and Meller, 2019).

The kurtosis index (Kg) indicates the stability of the dynamics of the current environment. The lowest value (0.11) obtained for Cgg horizon (72–150 cm) in profile no. 9 indicates pulsating changes in the energy of the environment during the deposition of the material. The highest value (0.50) of this index (profile no. 8, depth 17–39 cm) is the evidence of the high homogeneity of sedimentation conditions.

Table 3
Particle size distribution of mineral soils

Soil horizon	Depth (cm)	Percentage of fraction of diameter in mm				Texture class*	Sedimentological indices			
		Gravel > 2.0	Sand 2.0–0.05	Silt 0.05–0.002	Clay < 0.002		Mz (mm)	δ1	Sk_1	K_g
								phi		
Profile 7, PSC (2019): regosol próchniczny (węglanowy) / humic regosol (calcareous) WRB (2022): Calcaric Regosol (Anoarenic, Endoloamic, Drainic, Raptic, Mulmic)										
Aud	0–22	10	95	5	0	S sand	0.31	1.93	0.93	0.31
CAca	22–53	6	91	8	1	S sand	0.31	1.74	1.00	0.28
Cca	53–150	0	54	40	6	SL sandy loam	0.06	3.24	0.86	0.28
Profile 8, PSC (2019): gleba murszowata typowa / typical semimurshic soil WRB (2022): Haplic Umbrisol (Pantoarenic, Drainic, Humic)										
Au1	0–17	2	96	4	0	S sand	0.41	1.57	0.87	0.28
Au2	17–39	3	97	3	0	S sand	0.34	1.65	0.96	0.50
AC	39–57	4	94	6	0	S sand	0.39	1.54	0.97	0.33
C	57–150	4	98	2	0	S sand	0.25	1.68	0.81	0.30
Profile 9, PSC (2019): gleba deluwialna czarnoziemna gruntowo-glejowa / gleyic chernoziemic colluvial soil WRB (2022): Eutric Gleyic Arenosol (Sombric)										
Au	0–26	5	96	4	0	S sand	0.27	1.57	0.93	0.26
AC	26–60	7	96	4	0	S sand	0.27	1.57	1.07	0.35
Ahb	60–72	–	–	–	–	–	–	–	–	–
Cgg	72–150	3	98	2	0	S sand	0.41	1.23	0.76	0.11
Profile 10, PSC (2019): gleba gruntowo-glejowa torfiasta / mineral-peaty gleysol WRB (2022): Eutric Mollic Gleysol (Pantoarenic, Drainic)										
Ah	0–28	2	98	2	0	S sand	0.30	1.63	1.07	0.31
Cgg	28–41	1	99	1	0	S sand	0.23`	1.39	1.20	0.26
G	41–150	3	100	0	0	S sand	0.23	1.41	1.20	0.26
Profile 11, PSC (2019): gleba murszasta typowa (głęboko próchniczna) / typical postmurshic soil (deep humic) WRB (2022): Eutric Arenosol (Humic)										
Ad	0–38	8	93	7	0	S sand	0.28	1.80	0.88	0.29
Ab	38–67	10	93	7	0	S sand	0.25	1.71	0.84	0.23
ACb	67–81	7	94	6	0	S sand	0.29	1.68	0.87	0.30
C	81–150	8	97	3	0	S sand	0.29	1.52	1.00	0.26

* – according to USDA classification adopted by WRB (IUSS Working Group WRB 2022)

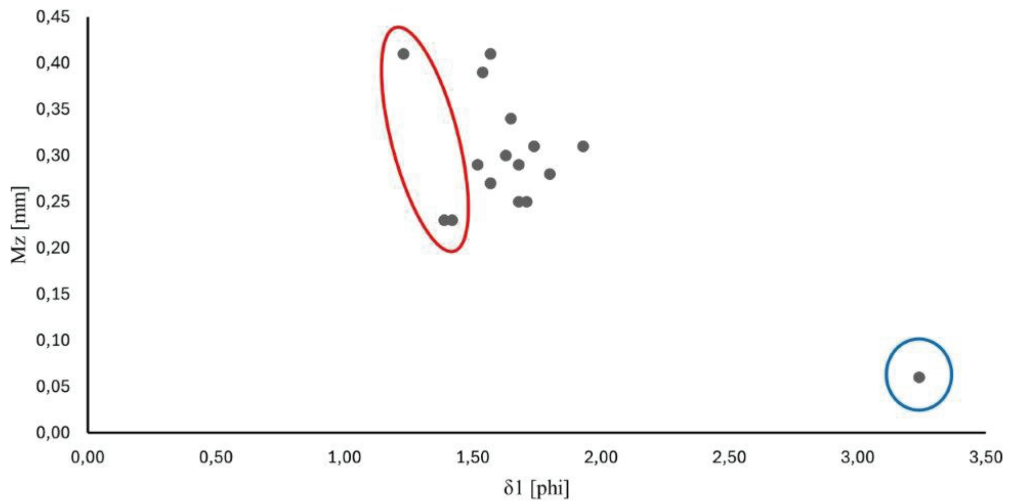

Fig. 3. Relationship between the mean grain size (Mz) and sorting degree (δ1) of the mineral soil materials (sandy lake sediments are marked red and sandy loam subsoil of profile no. 7 is marked blue)

It should be noted that loose sandy soil material does not physically protect SOM against microbiological decomposition (Wiesmeier et al., 2012). The accumulation of organic matter in the studied peatland-adjacent soils was determined mainly by water relations, where, due to the high groundwater level anaerobic conditions prevailed periodically in deeper layers. After drainage, the SOM in studied soils can be relatively easy mineralized.

4.3. Content of organic carbon and total nitrogen

The studied organic soils contain high, but typical, amounts of organic carbon and total nitrogen (Table 4). The highest total nitrogen contents (29.5 g kg^{-1}) were found in profile no. 3, in the Md mursh horizon (0–24 cm) and in Oi2 alder-rush peat horizon (92–150 cm). In peat soils (profiles no. 1, 2, 3, 5), as well as in mursh soils (profile no. 4), a decrease in the organic carbon at the same time an increase in the total nitrogen content are observed in the topsoil, which leads to a narrowing of the C:N ratio. This ratio is in the range of 13.7–16.1 in murshes, and distinctively wider in peats lying below (18.2–27.6). This is related to the fast oxidation of organic carbon compounds, with the release of CO_2 into the atmosphere, and accumulation of nitrogen in hardly decomposable humus compounds at the same time (e.g. Okruszko, 1993; Łachacz, 2001; Kalisz et al., 2010; Łachacz et al., 2023). The narrowing of the C:N ratio is one of the most important indicators of the intensity of the mursh formation (Leifeld et al., 2020; Kruczkowska et al., 2021; Lasota and Błońska, 2021). It should also be noted that significant amounts of total nitrogen were also found in gyttja soil (profile no. 6), and the C:N ratio in fine detrital gyttja (37–52 cm) was 9.2, whereas deeper it was in the range of 12.1–12.7. The wider C:N ratio (15.0) was stated in the surface horizon of coarse detrital gyttja, which should be associated with a greater share of vascular plant having floating leaves in the gyttja mass. Lacustrine algae are characterized by a narrower C:N ratio (ca. 3–9) than vascular plants (>15) (Meyers and Lallier-Vergès, 1999). Similar C:N ratios were found in gyttja soils of other sites in the Masurian Lakelands (Uggla, 1968; Łachacz and Nitkiewicz, 2021), as well as in other regions of the country (Meller, 2006; Markiewicz et al., 2015).

The soils accompanying organic soils have lower contents of organic carbon and total nitrogen, but it should be noted that this content also applies to deeper horizons. The enrichment of deeper horizons with organic matter is typical for sandy post-bog soils (semimurshic and postmurshic) (Łachacz, 2001; Łachacz and Załuski, 2023). The reasons for this should be associated with the origin of these soils, in which pedoturbation processes and the movement (illuviation) of dissolved humus compounds took place (Łachacz et al., 2023). It should be emphasized that organic matter accumulated in subsoil plays an important, but not fully recognized role in the terrestrial C cycle (Rumpel and Kögel-Knabner, 2011; Galluzzi et al., 2024; Labaz et al., 2024). These soils are characterized by a narrow C:N ratio (usually about 10–11), which is lower than in mursh horizons. The presence of organic matter in deeper soil horizons makes it somewhat isolated from contact with atmospheric air, and therefore less susceptible to microbiological decomposition. Anaerobic conditions (gleyic conditions) in the lower horizons of these soils also influence the slowdown in microbiological transformations.

4.4. Organic carbon stock

Due to the high content of SOM, the studied soils are characterized by a large organic carbon stock (Table 4). For five soil profiles of the organic order, organic carbon stock was calculated for soil horizons lying down to 150 cm, and for profile no. 2 to a depth of 91 cm, because below lacustrine marl with a negligible organic carbon content (as indicated by the LOI of

Table 4
Soil organic carbon stocks in the soil profiles

Depth [cm]	$C_{org.}$ [g kg^{-1}]	N_t	C:N	SD [g cm^{-3}]	BD	TP [%]	SOCstock [kg m^{-2}]
Profile 1, PSC (2019): gleba torfowa saprowa murszowa / sapric murshic peat soil WRB (2022): Drainic Sapric Histosol (Eutric)							
0–19	375.2	24.0	15.6	1.79	0.31	82.7	22.1
19–97	494.0	26.8	18.4	1.56	0.13	91.7	50.1
97–150	523.0	23.7	22.1	1.52	0.10	93.4	27.7
0–150							99.9
Profile 2, PSC (2019): gleba torfowa saprowa murszowa / sapric murshic peat soil WRB (2022): Drainic Sapric Histosol (Eutric)							
0–13	422.0	27.3	15.5	1.78	0.29	83.7	15.9
13–42	428.7	20.7	20.7	1.69	0.19	88.8	23.7
42–91	473.7	22.2	21.3	1.63	0.15	90.8	34.8
91–150	n.d.	n.d.	–	2.51	0.65	74.1	–
0–150							74.4

Table 4 – continue

Depth [cm]	$C_{org.}$ [g kg^{-1}]	N_t	C:N	SD [g cm^{-3}]	BD	TP [%]	SOCstock [kg m^{-2}]
Profile 3, PSC (2019): gleba torfowa fibrowa murszowa (saprowa) / fibric murshic peat soil (sapric) WRB (2022): Rheic Murshic Fibric Histosol (Eutric, Hyperorganic							
0–24	463.6	29.5	15.7	1.65	0.33	80.0	36.7
24–57	481.1	26.3	18.3	1.57	0.14	91.1	22.2
57–92	519.2	28.5	18.2	1.56	0.12	92.3	21.8
92–150	537.7	29.5	18.2	1.52	0.10	93.4	31.2
150–171	n.d.	n.d.	–	n.d.	n.d.	n.d.	–
171–200	n.d	n.d.	–	n.d.	n.d.	n.d.	–
200 +	n.d.	n.d.	–	n.d.	n.d.	n.d.	–
0–150				.			111.9
Profile 4, PSC (2019): gleba murszowa gytiowa limnowęglanowa / gyttja murshic soil (limni calcareous) WRB (2022): Calcaric Histic Gleysol (Drainic, Limnic)							
0–33	455.9	28.3	16.1	1.65	0.31	81.2	46.6
33–39	457.6	25.0	18.3	1.62	0.15	90.7	4.1
39–87	58.6	3.1	18.9	2.42	0.58	76.0	16.3
87–150	41.6	2.6	16.0	2.45	0.63	74.3	16.5
0–150							83.5
Profile 5, PSC (2019): gleba torfowa saprowa murszowa / sapric murshic peat soil WRB (2022): Murshic Sapric Histosol (Eutric)							
0–14	404.0	29.2	13.8	1.79	0.27	84.9	15.3
14–27	398.5	29.1	13.7	1.73	0.29	83.2	15.0
27–63	497.3	21.4	23.2	1.58	0.13	91.8	23.3
63–97	502.4	18.2	27.6	1.59	0.14	91.2	23.9
97–150	83.2	8.4	9.9	2.23	0.51	77.1	22.5
0–150							100.0
Profile 6, PSC (2019): gleba gytiowa limnowęglanowa / limni calcareous gyttja soil WRB (2022): Rheic Histosol (Eutric, Limnic)							
0–37	433.1	28.8	15.0	1.69	0.15	91.1	24.0
37–52	236.4	25.6	9.2	2.06	0.31	84.9	11.0
52–73	224.1	17.6	12.7	2.11	0.28	86.7	13.2
73–98	192.4	15.3	12.6	2.12	0.51	75.9	24.5
98–150	92.3	7.6	12.1	2.29	0.69	69.9	33.1
0–150							105.8
Profile 7, PSC (2019): regosol próchniczny (węglanowy) / humic regosol (calcareous) WRB (2022): Calcaric Regosol (Anoarenic, Endoloamic, Drainic, Raptic, Mulmic)							
0–22	85.7	11.6	7.4	2.36	0.72	69.5	12.2
22–53	7.6	1.0	7.6	2.51	1.35	46.2	3.0
53–150	5.3	0.2	26.5	2.50	1.43	42.8	7.3
0–150							22.5
Profile 8, PSC (2019): gleba murszowata typowa / typical semimurshic soil WRB (2022): Haplic Umbrisol (Pantoarenic, Drainic, Humic)							
4–0	495.8	23.6	21.0	1.52	0.12	92.1	2.4
0–17	65.2	5.9	11.0	2.48	0.81	67.3	8.8
17–39	71.4	6.2	11.5	2.41	0.73	69.7	11.1
39–57	13.9	1.0	13.9	2.56	1.52	40.6	3.6
57–150	n.d.	n.d.	–	2.59	1.57	39.4	–
0–150							23.5

Table 4 – continue

Depth [cm]	$C_{org.}$ [g kg^{-1}]	N_t	C:N	SD [g cm^{-3}]	BD	TP [%]	SOCstock [kg m^{-2}]
Profile 9, PSC (2019): gleba deluwialna czarnoziemna gruntowo-glejowa / gleyic chernoziemic colluvial soil WRB (2022): Eutric Gleyic Arenosol (Sombric)							
4–0	496.3	17.4	28.5	1.54	0.13	91.6	2.6
0–26	23.8	1.6	14.9	2.51	1.21	51.8	7.1
26–60	9.5	0.4	23.8	2.59	1.53	40.9	4.6
60–72	75.3	4.9	15.4	2.38	0.94	60.5	8.5
72–150	7.2	0.4	18.0	2.60	1.54	40.8	8.4
0–150							28.6
Profile 10, PSC (2019): gleba gruntowo-glejowa torfiasta / mineral-peaty gleysol WRB (2022): Eutric Mollic Gleysol (Pantoarenic, Drainic)							
5–0	473.9	22.2	21.3	1.52	0.11	92.8	2.6
0–28	56.5	5.2	10.9	2.47	1.10	55.5	17.0
28–41	n.d.	n.d.	–	2.56	1.59	37.9	–
41–150	n.d.	n.d.	–	2.56	1.62	36.7	–
0–150							17.0
Profile 11, PSC (2019): gleba murszasta typowa (głęboko próchniczna) / typical postmurshic soil (deep humic) WRB (2022): Eutric Arenosol (Humic)							
0–38	14.3	1.3	11.0	2.50	1.44	42.4	7.2
38–67	19.3	1.8	10.7	2.52	1.32	47.6	6.6
67–81	10.2	0.9	11.3	2.56	1.53	40.2	2.0
81–150	n.d.	n.d.	–	2.61	1.64	37.2	–
0–150							15.8

SD – specific density; BD – bulk density; TP – total porosity; n.d. – not determined

1.1%) occurs. It should be noted that below 150 cm there are also soil materials containing significant amounts of organic carbon, however, assuming a thickness of 150 cm for these calculations enables comparison of the soils studied. Organic carbon stock in the studied organic soils ranges from 74.4 kg m^{-2} (profile no. 2) to 111.9 kg m^{-2} (profile no. 3). The highest values of organic carbon stock were found in peat soils, in which the entire profile was composed of peat. Lower values were stated in the soils with limnic materials in the lower parts of the profile (lacustrine marl, proper lacustrine marl, clay-calcareous gyttja) and thus with lower organic carbon content and higher $CaCO_3$ content. It should be noted, however, that gyttja soils composed of detrital gyttja (profile no. 6) are characterized by a large organic carbon stock (105.8 kg m^{-2}), comparable to typical peat soils.

Organic carbon stock in soils accompanying organic soils in the landscape is correspondingly lower, but still high compared to typical autogenic soils developed from mineral materials (Wiesmeier et al., 2012; Świtoniak, 2023). This results from two conditions: one is the occurrence of organic matter in deeper soil layers, and the other is the higher bulk density of these soils. In calculating SOCstock for the soil profiles (0–150 cm) with epihumus layer (forest litter) (profiles nos. 8, 9, and 10) the superficial layers were excluded. Although epihumus layers contain large amounts of organic carbon, it is of different nature and only a small part of this carbon may enter the mineral soil below. To sum up, it can be stated that organic carbon stock in these soils for entire soil profile can constitute from 1/4 to 1/3 of the stock found in organic soils (in the 0–150 cm layer). Therefore, in estimating organic carbon stock, both on a local and global scale, it is necessary to include those soils that, due to the fact that they usually occupy narrow ecotone areas, are often underestimated in terms of area. Among the soils studied, a large organic carbon stock (28.6 kg m^{-2}) in gleyic chernozem colluvial soil (profile no. 9) and in typical semimurshic soil (23.5 kg m^{-2}) (profile no. 8) is noteworthy. The remaining soils have a lower organic carbon stock ranging from 15.8 to 22.5 kg m^{-2}. The organic carbon stocks of studied soils are similar to southeast Germany soils (Histosols, Gleysols) (Wiesmeier et al., 2012).

5. Conclusions

1. In the vicinity of the Łuknajno lake, as a result of bioaccumulation of bottom lake sediments and then peats, the soils that belong to the organic soil order in the Polish Soil Classification, 6th ed., (2019) were formed. Four of these soils belong to the peat soil type, one to the mursh soil type and one to the gyttja soil type.
2. Organic soils are accompanied by soils rich in organic matter (near-peat soils) belonging to mineral-peaty gleysol, gleyic chernoziemic colluvial soil, humic regosol (calcareous), typical semimurshic soil, typical postmurshic soil (deep humic). The origin of these soils is related to a high groundwater level, which slowed down the rate of mineralization of SOM, which accumulated in humus horizons, usually of great thickness.
3. Due to the shallow deposition of calcareous gyttja in the lake and the high content of $CaCO_3$ in the catchment soils, the studied soils contain significant amounts of calcium carbonate and are neutral or slightly acidic at the surface (pH in H_2O 6.4–7.0), and alkaline deeper (pH in H_2O 7.1–8.6).
4. The C : N ratio in peat horizons is 18.2–27.6, and in mursh horizons it is clearly narrower (13.7–16.1), which indicates the ongoing mineralization processes of soil organic matter.
5. Organic carbon stock in the studied profiles of organic soils to a depth of 150 cm ranges from 74.4 kg m^{-2} to 111.9 kg m^{-2}. Organic carbon stock in soils accompanying organic soils in the landscape is lower (15.8–28.6 kg m^{-2} for entire soil profile), but clearly higher than that stock in mineral sandy soils. Therefore, in estimating organic carbon stock, these soils should be included, despite their small and scattered areas.

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Gleby organiczne i inne gleby zasobne w materię organiczną w otoczeniu jeziora Łuknajno (Rezerwat Biosfery Jeziora Mazurskie, NE Polska)

Słowa kluczowe

Jezioro Łuknajno
Gleby torfowe
Gleby gytiowe
Gleby pobagienne
Systematyka gleb
Zasoby węgla organicznego

Streszczenie

Badaniami objęto bezpośrednie otoczenie jeziora Łuknajno. Pokrywa glebowa tego obszaru jest uwarunkowana stosunkami wodnymi, tj. wysokim poziomem wody gruntowej. Opisano jedenaście profili glebowych i w pobranym materiale glebowym oznaczono: uziarnienie (w materiałach mineralnych), zawartość węglanów, odczyn, zawartość węgla organicznego i azotu ogółem, gęstość fazy stałej i gęstość objętościową, porowatość ogólną, zasoby węgla organicznego w profilu glebowym. Zgodnie z Systematyką gleb Polskich (2019), sześć profili glebowych zostało zaliczone do rzędu gleb organicznych (cztery profile do typu gleb torfowych, jeden do typu gleb murszowych i jeden do typu gleb gytiowych). Profile gleb mineralnych towarzyszących w krajobrazie glebom organicznym zostały sklasyfikowane jako: gleba gruntowo-glejowa torfiasta, gleba deluwialna czarnoziemna gruntowo-glejowa, regosol próchniczny (węglanowy), gleba murszowata typowa, gleba murszasta typowa (głęboko próchniczna). Według klasyfikacji WRB (2022), pięć profili zaliczono do Histosols (Drainic Sapric Histosols, Murshic Fibric Histosols, Murshic Sapric Histosols, Rheic Histosols). Gleby mineralne zasobne w SOM, towarzyszące w krajobrazie glebom organicznym zaliczono do: Calcaric Histic Gleysols, Calcaric Regosols, Haplic Umbrisols, Gleyic Arenosols, Mollic Gleysols, Eutric Arenosols. Właściwości badanych gleb uwarunkowane są dużą zawartością węglanu wapnia, który został wymyty z gleb zlewni i zakumulowany w basenie jeziora Łuknajno w postaci miąższych pokładów gytii węglanowej. Cechą charakterystyczną badanych gleb są duże zasoby węgla organicznego. W glebach organicznych zasoby te wynoszą od 74.4 do 111.9 kg $C_{org.}$ m^{-2} (w profilu glebowym do 150 cm). Gleby mineralne towarzyszące glebom organicznym w krajobrazie mają zasoby węgla organicznego w przedziale 15.8–28,6 kg m^{-2}, to jest istotnie wyższe niż autogeniczne gleby mineralne. Dlatego w celu szacowania zasobów węgla organicznego należy uwzględniać te gleby pomimo, że zwykle zajmują małe i rozproszone areały.