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Chemical properties of small peatlands deposits (Eastern Polesie)**

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A b s t r a c t. In view of the extremely important role of wetlands, an attempt was made to determine the state of preservation of peat forming processes as a condition for the proper functioning of those areas. By addressing this question, we hoped to determine whether the peat bogs and mires of the Łęczna-Włodawa Plain currently act as carbon sources. The aim of the present study was to compare the ash content and the contents of selected macro- and micronutrients in the deposits. The research was carried out in the years 2010-2013 and covered eight peatland areas (three mid-field and five mid-forest peatlands). The ash content, as well as the content of biogens, and selected macro- and micronutrients of the studied deposits varied and depended on the type of the deposit forming a given layer. In all the studied deposits, the carbon content was high, especially in the transitional *Sedge-Sphagnum* peat and the raised pine peat. The marsh layers, in relation to the studied peat minerals and gyttja, were characterized by a lower carbon content, and the restriction of C:N and N:P ratios. In all the studied peat bogs, located in the Łęczna-Włodawa Plain, the accumulation phase dominated, so they do not act as carbon suppliers.

K e y w o r d s: organic deposits, macronutrients, micronutrients, lithology

INTRODUCTION

Wetlands are one of the most important elements of the structure of the natural environment. On the one hand, they play a role in shaping the landscape and, on the other hand, they take part in the water cycle. They are reservoirs of water and regulate the outflow of water in terms of its volume and distribution. These areas also affect the balance of chemical elements. This is especially true for carbon and nitrogen, but also for calcium, magnesium and phosphorus (Whiting and Chanton, 2016; Yu, 2012). It is estimated that, despite the small area occupied by peatlands (3 to 4% worldwide, 5.5% in Europe, and 4.2% in Poland) (Lipka and Stabryła, 2012; Oleszczuk, 2012), they form a huge depository of soil carbon in the natural environment, as they store about 30% of the world's pool of this element (Ilnicki, 2002; Montanarella *et al*., 2006; Garneau *et al*., 2014). In Poland, there are large regional differences in the size of the peat cover, with the smallest peatland areas found in the southern and central regions of Poland, and the largest in North-Eastern Poland (about 12%) (Dobrowolski and Lewandowski, 1998). According to Dembek (2000), the Łęczna-Włodawa Plain holds vast deposits of peat. Documented peat beds with an area exceeding 1 ha occupy 21.1% of the surface of the Plain, and include raised bogs – 1.07% and transitional mires (poor fens) – 1.74 ha. For this reason, the Łęczna-Włodawa Plain undoubtedly has an effect on the climate of this part of Europe

Under natural conditions, undrained peat soils absorb carbon dioxide from the atmosphere through plant photosynthesis, trapping this gas and forming reservoirs of it, while at the same time emitting methane. When these areas are drained, for instance, for agricultural use, they cease to emit methane and start to release carbon dioxide and nitrous oxides, gradually turning into emitters of greenhouse gases (Goraj *et al*., 2013; Stępniewska *et al*., 2004; Turbiak and Jaszczyński, 2011; Ilnicki, 2002).

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Through intensive gas exchange, wetlands contribute to climate change. They are sites of an intensive migration of chemical elements. Biogenic deposits, especially peats with high filtering properties, accumulate nutrients and purify water by trapping and binding it in plants.

The growth and development of vegetation depends on three basic elements, *i.e.* water, light and nutrients. The availability of these factors determines what vegetation can grow in a given ecosystem. This can be clearly seen in peat ecosystems, which are dominated by some species of narrowly specialized plants that are capable of developing in acidic, highly hydrated environments, with restricted access to oxygen in the root zone and nutrient deficiencies. Peatland plants have developed a number of adaptations to such conditions, among others, aerenchyma, the ability to adjust enzyme activity under the conditions of a low content of oxygen, the ability to open alternative metabolic pathways leading to the formation of less toxic products (e.g. malic acid, butyric acid), or the formation of shallower roots in order to shorten the oxygen transport pathway (Gliński and Stępniewski, 1985; Marschner, 1986; Flessa and Fischer, 1992; Chestworth, 2004; Evans, 2004). The nutrients necessary for the plants to develop move deeper into the soil profile, thus becoming inaccessible to plant roots. Migration is dependent on many factors, such as the soil's cation exchange capacity (Harter, 1991), the moisture content (Or *et al.*, 2007) and pH. For example, under acidic conditions (pH less than 6.5), iron and aluminum oxides bind bioavailable phosphorus, while pH above 7 and high calcium contents promote the formation of insoluble calcium phosphate (Raghotham, 2005; McDowell *et al.*, 2001). The presence and availability of some macro- and micronutrients in peatlands depend on geological factors (calcium, magnesium), the inflow with waters nourishing the peatland (phosphorus, nitrogen), and human activity (aluminum, iron, cadmium).

Transitional mire and raised bog habitats are poor in nutrients, which is why they are sensitive to changes in the nutrient content. Studies on oligotrophic peatlands have shown that both the plant growth and development are limited by nitrogen, so even a minimal increase in the nitrogen content results in the over fertilization of a habitat (Wendel *et al.*, 2011) and reed overgrowth. Recently, however, it has been pointed out that phosphorus is responsible for the loss of plant species in land ecosystems to a greater degree than nitrogen (Wassen *et al.*, 2005; Wendel *et al.*, 2011; Ceulemans *et al.*, 2013).

Wetlands, and particularly small wetland areas located in forests and fields, are extremely vulnerable to anthropogenic pressure, mainly from agriculture. This is primarily so because farming has an influence on water quality, and in the case of wetlands this factor determines their very existence and development. Intensive farming leads to the enrichment of the environment with large quantities of biogens (among others, nitrogen and phosphorus) which, together with the surface runoff, reach the waters supplying wetlands. This leads to eutrophication, causing the disappearance of small mires (Waldon, 2012) which fulfill a variety of functions in the agricultural landscape. They retain water, provide a habitat for plants and animals, constitute ecological corridors, diversify the agricultural landscape, contribute to biodiversity, as well as shape the regional climate (Grootjans and Wołejko, 2007; Lamentowicz, 2007; Łachacz, 2004; Łachacz and Olesiński, 2000). Despite this fact, small woodland and field marshlands are still commonly perceived as constituting a barrier to the development of agriculture – an obstacle that needs to be removed. Organizations such as the UN, the Ramsar Convention Bureau (2014), are making efforts to draw public attention to the role of these ecosystems through various social campaigns.

The aim of the present study was to compare the ash content, and the contents of selected macro- and micronutrients in the (peat/gyttja) deposits of several small peatlands. In view of the extremely important role of wetlands, an attempt was made to determine the state of preservation of peat forming processes as a condition for the proper functioning of those areas. By addressing this question, we hoped to determine whether the mid-forest and mires/midfield peatlands of the Łęczna-Włodawa Plain are currently acting as carbon sources.

MATERIAL AND METHODS

The research was carried out in the years 2010-2013 and covered eight peatland areas (three mid-field and five mid-forest peatlands) (Table 1, Fig. 1). In terms of physical geography, these sites are situated in the Łęczna-Włodawa Plain, which is a mesoregion of West Polesie (Polesie Zachodnie) (Kondracki, 2002).

From the point of view of the division of the Lublin region into peatland areas, the investigated peatlands are located in the Chełm-Włodawa area, which has the largest peatland cover in the Lublin region (Borowiec, 1990).

A detailed lithological analysis of the deposits of each site was based on an exploration drill grid. The drills were done along orthogonal transects (N-S, W-E) at 50 m intervals. For further investigations, two points representative of each site were identified, and an INSTORF core sampler (50 cm long with a core drill bit diameter of 5 cm) was used to extract core samples reaching down to the mineral bottom. Chemical analyses of the deposits were performed using the method developed by Sapek and Sapek (1997). The samples were mineralized with a mixture of acids (HNO_3, d = 1.40, $HClO_4$, 60%, mixed in a 20:5 volume ratio), and then assayed for the total contents of sodium, potassium, phosphorus, calcium, magnesium, iron and manganese, using the flame atomic absorption spectroscopy (FAAS). Total nitrogen was determined by the Kjeldahl method (Rowell, 1994), and total carbon was

Table 1. Characterization of the investigated peatland areas

Area (ha)	Altitude (m a.s.l.)	Max depth sediments (cm)	Number of object/Current vegetation	Land use around the peat bog
			Mid-field peatlands	
			1 Albertów (N 51º17'42.8" E 23º04'16.9")	
7.1	173	370	*Rhynchosporetum albae*, *Sphagno-Caricetum rostratae*, *Caricetum lasiocarpae*, com. with *Menyanthes trifoliate Calla palustris*, *Eriophorum angustifolium* and *Eriophorum vaginatum-Sphagnum fallax*	Pine and birch grove, approx. 40 years old, arable land, grassland, drainage ditches
			2 Ostrówek Podyski (N 51º21'13.7" E 23º09'01.4")	
44.0	172	270	*Caricetum rostratae*, *Sphagno-Caricetum rostratae*, *Caricetum lasiocarpae*, *Caricetum diandrae*, *Ledo-Sphagnetum*, *Vaccinio uliginosi-Pinetum*, com. with *Sphagnum cuspidatum*, *Menyanthes trifoliata*, *Calla palustris*, *Eriophorum angustifolium* and *Eriophorum vaginatum-Sphagnum fallax*	Arable land, grassland, pine grove, drainage ditches
			3 Jelino (N 51º25'08.7"E 23º01'50.7")	
8.9	168	240	*Warnstorfietum exannulatae*, *Rhynchosporetum albae*, *Sphagno-Caricetum rostratae*, *Caricetum lasiocarpae*, *Caricetum diandrae*, com. with *Sphagnum cuspidatum*, *Calla palustris*, *Eriophorum angustifolium* and *Eriophorum vaginatum-Sphagnum fallax*	Arable land, building, the object is part of the Natura 2000 area
			Mid-forest peatlands	
			4 Podlaski (N 51º26'05.7" E 23º28'20.9")	
1.3	168	230	*Caricetum rostratae*, *Sphagno-Caricetum rostratae*, *Caricetum lasiocarpae*, *Caricetum diandrae*, *Ledo-Sphagnetum*, *Vaccinio uliginosi-Pinetum*, com. with *Menyanthes trifoliata*, *Calla palustris*, *Eriophorum angustifolium* and *Eriophorum vaginatum-Sphagnum fallax*	Associations and communities from the *Vaccinio-Piceetea* classes
			5 Krasne (N 51º24'34,0" E 22º57'28.9")	
2.5	166	160	*Caricetum rostratae*, *Sphagno-Caricetum rostratae*, *Rhynchosporetum albae Caricetum lasiocarpae*, *Ledo-Sphagnetum*, *Vaccinio uliginosi-Pinetum*, com. with *Menyanthes trifoliata*, *Calla palustris*, *Eriophorum angustifolium* and *Eriophorum vaginatum-Sphagnum fallax*	Forest associations and communities from the *Vaccinio-Piceetea* and *Alnetea glutinosae* classes
			6 Macoszyn (N 51º23'26.5" E 23º27'36.2")	
2.0	173	130	*Caricetum rostratae*, *Sphagno-Caricetum rostratae*, *Rhynchosporetum albae Caricetum lasiocarpae*, *Vaccinio uliginosi-Pinetum*, com. with *Sphagnum cuspidatum*, *Menyanthes trifoliata*, *Calla palustris*, *Eriophorum angustifolium* and *Eriophorum vaginatum-Sphagnum fallax*	Forest associations from the *Vaccinio-Piceetea* class (piece of *Molinio-Pinetum* and *Leucobryo-Pinetum*)
			7 Stulno (N 51º22'57.7" E 23º36'56.8")	
2.9	168	300	*Rhynchosporetum albae Sphagno-Caricetum rostratae*, *Caricetum lasiocarpae*, com. with *Calla palustris*, *Eriophorum angustifolium* and *Eriophorum vaginatum-Sphagnum fallax*	Associations from the *Vaccinio-Piceetea* class (piece of *Molinio-Pinetum* and *Leucobryo-Pinetum*)
			8 Osowa (N 51º24'58.2" E 23º33'48.9")	
2.8	170	250	*Sphagno-Caricetum rostratae*, com. with *Calla palustris*, *Eriophorum angustifolium* and *Eriophorum vaginatum-Sphagnum fallax*	Associations from the *Vaccinio-Piceetea* class (piece of *Vaccinio uliginosi-Pinetum, Molinio-Pinetum*, *Leucobryo-Pinetum*) and Associations from the *Alnetea glutinosae* class

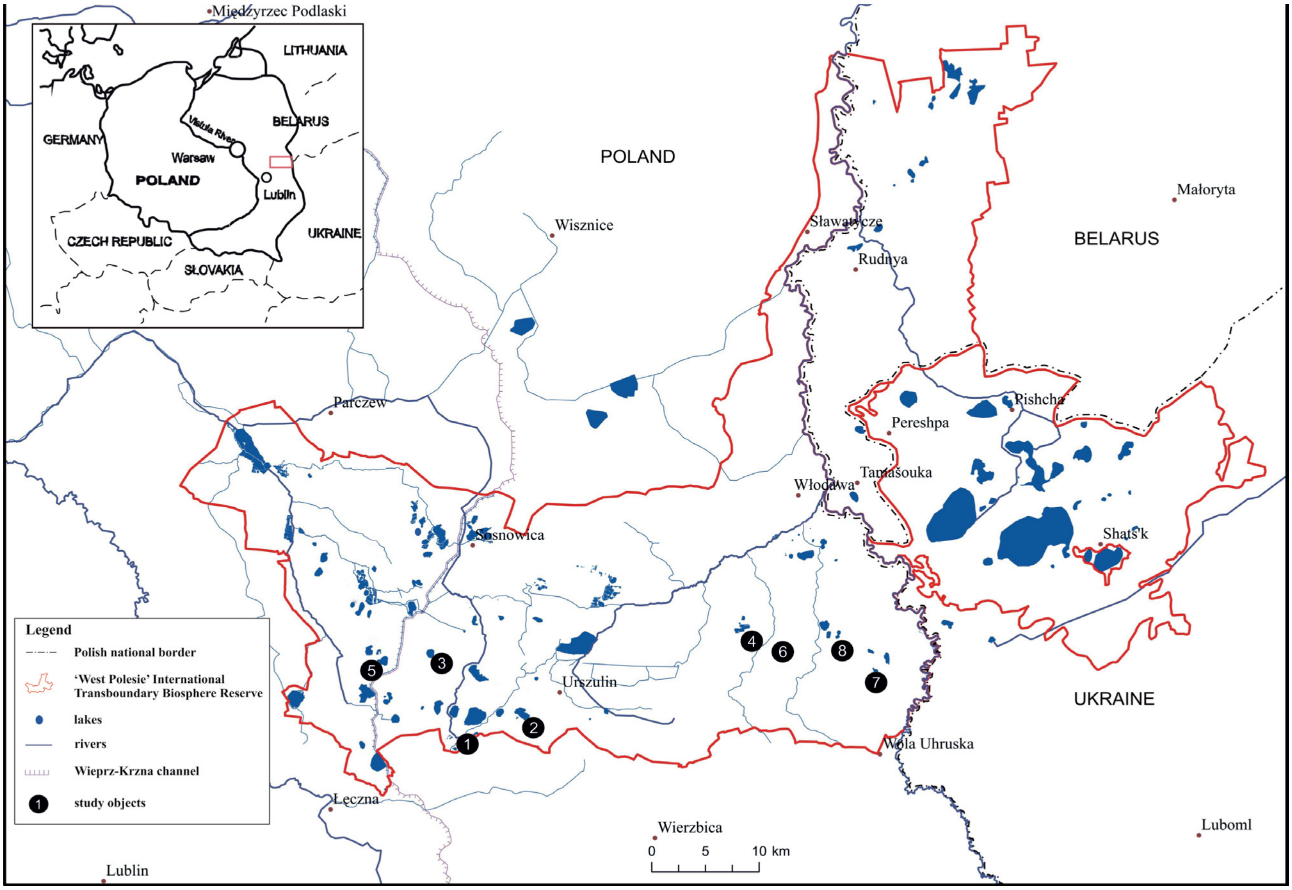

Fig. 1. Studied area (own study based on ArcGis Basemap Imagery). Name of objects as in Table 1.

measured by infrared spectrometry. In addition, pH was measured directly in the peat material by the potentiometric method, using an Elmetron CX-731 pH meter with a compatible Ag/AgCl/KCl electrode. The ash content was determined by loss-on-ignition during the combustion of 1 g of the peat sample at 560°C. The deposits found in the bottom layer of the studied peat beds were dated by the radiocarbon method in the Radiocarbon Laboratory of the Institute of Physics at the Silesian Technical University in Gliwice. Radiocarbon dates were calibrated with OxCal 4.1 software (Ramsey, 2001) using the IntCal09 calibration curve (Reimer *et al.*, 2009) Macoszyn and Stulno sites, and the IntCal13 calibration curve (Reimer *et al*., 2013) Osowa site.

The peats were classified in accordance with the Polish Standard (PN-85/G-02500 Peat. Genetic Division of the Raw Material). The lithological characteristics of the analyzed cores were described using the Troels-Smith method (Troels-Smith 1955). Diagrams showing the lithological structure of the examined cores were made using POLPAL ver. 2012.05 software.

The results were analyzed statistically (ANOVA, regression analysis) using Statistica 12.0 software (StatSoft Polska). The results for deposit samples classified as the same type were calculated as mean values. Differences were statistically significant at $p \leq 0.05$. In order to determine the relationship between peat types and the contents of selected elements, the Spearman rank correlation was used.

RESULTS

The stratigraphic profiles for all the investigated sites contained limnic deposits and peats. The uppermost (30 to 80 cm thick) layer of the analyzed deposits consisted of very poorly decomposed (5-10%) transitional or raised peat types. In some samples, the topmost layer contained moorsh (peat humus) (parts of the Ostrówek Podyski and Jelino peatland). Layers built of sedge fen peats (sedge-moss, sedge, moss, and sedge-reed peat types) were found below, with gyttja admixture and very strong hydration. In some of the analyzed profiles, a layer of water with gyttia plant remains was also observed (Fig. 2). The bottom parts of some of the analyzed deposits were created from sediments reflecting limnic accumulation (gyttja). The lowermost layer was usually clayey gyttja, which transitioned upward into organic-mineral gyttja, and then into organic (detritus) gyttja. These parts of gyttja were watered down, semi-liquid, gelatinous, usually gray-brown with a thickness of up to 1 m. In some profiles, a well-developed layer

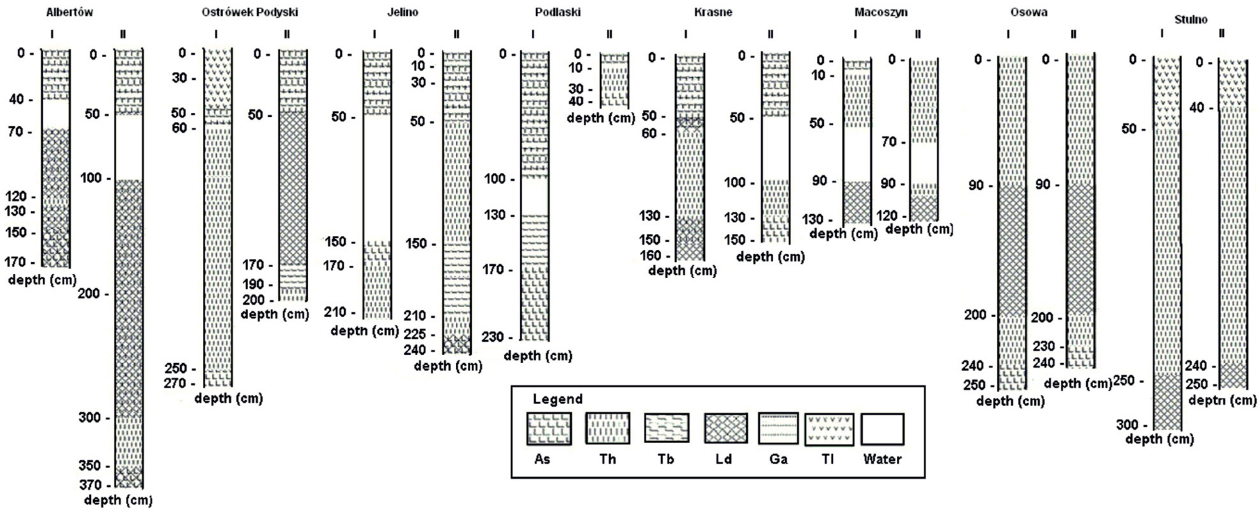

Fig. 2. Lithological characteristics of the deposits found in the profiles As – *Argilla steatodes*, Tb – *Turfa bryophytica*, Th – *Turfa herbacea*, Tl – *Turfa lignose*, Ld – *Limnus detriuosus*, Ga – *Granna arenosa* (marks acc. to Tobolski, 2000).

of moss peat was found under gyttja, at the contact with the mineral bottom or mineral-organic gyttja (Macoszyn I, II, Podlaski I). Less often, moss peats overlay sedge peats (Ostrówek Podyski I, II, Jelino I, II).

The results of radiocarbon analysis indicated that the oldest deposits came from Ostrówek Podyski. The age of the layer extracted from a depth of 235-240 cm was determined at 12210 ± 110 BP, which was the Late Vistulian glaciation, and more specifically the warming phase – the Bölling Interstadial. Deposits extracted from the 235-240 cm layer of the Krasne peat bog were dated at 11320 ± 120 BP. This date shows that they originated in the late Alleröd and the Younger Dryas. The age of the deposits drilled in Osowa (depth of 235-240 cm) was 10 600 ± 150 BP, which means that they formed in the Younger Dryas. Deposits extracted from the 205-210 cm layer of the Macoszyn site were dated at 10050 ± 130 BP. This date indicates they came from the Preboreal. The organic material started to accumulate in the Podlaski peat bog (layer at 235-240 cm) 9430 ± 95 BP, in Jelino – 9250 ± 180 BP, and in Stulno (layer at 240-245 cm) 9360 ± 60 BP. These dates indicate the deposits formed in the first half of the Boreal period. In the Albertów peat bog, accumulation of biogenic deposits started 6200 ± 900 BP, *i.e.* in the first half of the Atlantic period (Table 2).

The peat deposits found in the studied peat beds had a range of pH values from strongly to slightly acidic. The pH (in H_2O) ranged from 3.67 to 4.70 in the samples of transitional peat (sedge – S*phagnum* and cotton grass – S*phagnum* types, respectively), and from 3.62 to 5.17 for the remaining peat types. The raised pine peat deposits displayed a narrow pH range of 4.00 to 4.09, while the deposits of raised cotton

Table 2. Results of the radiocarbon dating of the peat samples, expressed as conventional ^{14}C age

Study object	Depth (cm)	Age ^{14}C (BP)	Calendar age (calibrated) range 68%	Calendar age (calibrated) range 95%
Albertów	295-300	6200 ± 900	8050 – 6000 cal BP (68.2%)	9450 – 5050 cal BP (95.4%)
Ostrówek Podyski	235-240	12210 ± 110	14460 – 14430 cal BP (1.7%) 14380 – 14360 cal BP (0.6%) 14240 – 13850 cal BP (65.9%)	14860 – 14710 cal BP (3.8%) 14640 – 13790 cal BP (91.6%)
Jelino	220-225	9250 ± 180	10680 – 10230 cal BP (68.2%)	11100 – 10230 cal BP (92.7%) 10070 – 9930 cal BP (2.7%)
Podlaski	235-240	9430 ± 95	11060 – 11035 cal BP (3.6%) 10990 – 10975 cal BP (1.6%) 10790 – 10510 cal BP (63.0%)	11095 – 10415 cal BP (95.4%)
Krasne	145-150	11320 ± 120	13320 – 13100 cal BP (68.2%)	13430 – 12900 cal BP (95.4%)
Macoszyn	125-130	10050 ± 130	11820 – 11320 cal BP (68.2%)	12060 – 11230 cal BP (95.4%)
Stulno	270-275	9360 ± 60	10670 – 10505 cal BP (68.2%)	10745 – 10405 cal BP (95.4%)
Osowa	235-240	10600 ± 150	12710 - 12380 cal BP (67.0%) 12260 – 12250 cal BP (1.2%)	12760 – 12050 cal BP (95.4%)

grass – S*phagnum* peat had pH values ranging from 3.81 to 4.56. The low moor sedge peat was characterized by a pH range of 4.01 to 5.73, while the pH of *Hypnum*-moss peat ranged from 3.89 to 5.01. Organic gyttja was characterized by an acidic pH (4.23-4.99, in H_2O). The moorsh top layers of peat had a strongly acidic pH (from 3.50 to 3.85, in H_2O) (Table 3). A positive correlation (R = 0.57***) was found between peat type and pH.

The ash content of the examined deposits varied and depended on the type of the deposit forming a given layer. A correlation was established between the deposit type and the ash content (R = −0.34**). The ash content ranged from 1.90 to 8.44% in the sedge – *Sphagnum* transitional peat, and from 1.95 to 32.45% in the cotton grass – *Sphagnum* peat. The low moor sedge peat was characterized by an ash content in the range of 2.50-44.1%, and the *Hypnum* – moss peat had an ash content of 3.40-22.70%. Raised bog peats, both pine and segde – *Sphagnum* type, had the lowest ash contents in the range of 9.80-13.4 and 3.10-9.93%, respectively. The top layers of moorsh contained from 9.63 to 11.00% of ash. Slightly higher ash contents were recorded in the organic gyttja samples (10.05-16.25%) (Table 3).

The contents of monovalent sodium and potassium were varied. The lowest contents of both elements were found in the organic gyttja samples (mean contents of 0.42 and 0.45 g kg^{-1}, respectively), and the highest in the layers of low moor sedge peats (the mean contents of 1.13 and 0.58 g kg^{-1}, respectively) and *Hypnum*-moss peats (the mean contents of 1.11 and 0.67 g kg^{-1}, respectively) (Table 3). The sodium content was positively correlated with the type of the deposit (R = 0.25*) and negatively with pH (R = −0.43**). The potassium content was negatively correlated with pH (R = −0.34*) (Table 4).

In the analyzed profiles, the average content of calcium in the transitional peat was in the range of 4.91 to 5.63 g kg^{-1} (sedge – *Sphagnum* and cotton grass–*Sphagnum* peats, respectively). The highest content of calcium (7.10 g kg^{-1}) was found in the raised bog type pine peat. The content of magnesium in the analyzed profiles was quite low and did not exceed 1.00 g kg^{-1}, with an exception of the organic gyttja samples which contained, on average, 1.30 g kg $^{-1}$ of this element (Table 3).

The mean content of iron in the analyzed deposits was varied and ranged from 1.12 g kg^{-1} in the samples of the raised bog type pine peat to 4.07 g kg^{-1} in the sedge fen peat samples. A correlation was established between the iron content and pH (R = 0.14*) (Table 4).

The manganese content was also different for the various deposits, and it correlated positively with pH (R = 0.21*). The highest content of manganese (a mean of 108.16 mg kg^{-1}) was found in raised cotton grass – *Sphagnum* peat, and the lowest content of this element (a mean of 8.04 mg kg^{-1}) was determined in raised pine peat. The sedge – *Sphagnum* and cotton grass – *Sphagnum* transitional peats were characterized by similar manganese contents of 43.36 and 47.74 mg kg^{-1}, respectively. The contents of manganese found in the fen peat were half as low as those observed in the transitional peat. The mean manganese contents in gyttja and moorsh deposits were very similar (16.53 and 16.51 mg kg^{-1}, respectively) (Table 3).

The content of biogens (nitrogen and phosphorus) was dependent on both the deposit type (R = 0.36**, R = -0.62***) and pH (R = -0.21*, R = 0.48**) (Table 4). The average nitrogen content ranged from 11.0 g kg^{-1} in the cotton grass – *Sphagnum* transitional and raised peats, through 16.0 g kg^{-1} in the raised pine peat and moorsh, to 36.26 g kg^{-1} in the floor layers formed by sedge – *Sphagnum* transitional peats. The phosphorus content ranged from 0.23 g kg^{-1} in the raised pine peat and the low moor peat deposits of both the *Hypnum* and sedge types, to 0.62 g kg^{-1} for moorsh (Table 3).

The mean total carbon content (in peats with the predominance of organic carbon) was the highest in the sedge – *Sphagnum* transitional peat (577.84 g kg^{-1}). Among the various peat deposits, the lowest carbon content was found in the raised cotton grass – *Sphagnum* peat (396.79 g kg^{-1}). The uppermost layers of moorsh had the lowest overall carbon content of 117.51 g kg^{-1}. A correlation between the deposit type and the carbon content was observed (R = −0.36*).

DISCUSSION

The results obtained in the present study indicate that the analyzed peatlands differ with respect to the ash content, pH, and the content of macro- and micronutrients.

The acidity of the analyzed deposits is similar to peatlands found in the eastern regions of Poland. For example, the peats forming mires surrounding Moszne Lake have an acidic pH (3.87 – 4.12) (Tokarz *et al.*, 2015). Malawska *et al.* (2006) found a strong correlation (r^2 = 0.8) between the ash content and pH. The studies conducted in the peatlands of the Łęczna-Włodawa Plain did not confirm that such a correlation existed. The low pH may be caused by peat-forming sphagnum mosses properties, as well as acid rains. *Sphagnum* mosses have the ability to reduce pH by releasing protons from carboxyl groups and replacing them with other elements. The hydrogen released into the ground waters reduces the pH (Clymo, 1967; Gorham and Cragg, 1960). An acidic pH is also a defense mechanism against microorganisms. It has been demonstrated that *Sphagnum papillosum* secretes into the surrounding environment phenolic compounds which have an antibacterial effect, and that the acidic pH provides conditions appropriate for active, undissociated forms of these compounds (Mellegard *et al.*, 2009).

An important parameter affecting the water-air conditions is the ash content (Wiłkomirski and Malawska, 2004). The ash content determination is a simple method for estimating carbon losses in a profile (Rogiers *et al.*, 2008;

Table 3. Means of chemical parameters by peat types (botanical origin) and study objects

Study object	Depth (cm)	pH		Ash content (%)	P	K	Na	Ca	Mg	Fe	N	C	Mn (mg kg^{-1})	C/N	N/P
		H_2O	KCl		(g kg^{-1})										
Transitional Sedge - *Sphagnum* peat															
Albertów I	0-40	4.70	3.09	5.03	0.44	0.50	0.24	4.87	0.93	0.82	8.00	459.43	51.83	57.43	18.18
Jelino II	50-80	4.03	3.18	1.90	0.11	0.09	0.67	1.59	0.05	0.16	19.10	543.70	53.00	28.47	173.64
Krasne I	50-60	3.90	2.99	2.90	0.38	0.31	0.81	3.14	0.34	1.66	14.70	556.70	29.60	37.87	38.68
Macoszyn II	0-70	3.95	3.00	3.61	0.37	0.61	0.66	2.23	0.31	3.77	132.77	481.03	60.79	3.62	358.84
Osowa I	0-60	4.27	3.50	2.73	0.33	0.86	0.61	9.76	0.5	1.95	21.4	951.9	44.56	44.48	64.85
Osowa II	40-80	3.67	3.00	8.44	0.37	0.37	0.26	7.89	0.27	2.27	21.60	474.31	20.40	21.96	58.38
Transitional cotton grass - *Sphagnum* peat															
Albertów II	0-50	5.04	4.81	32.45	0.49	0.82	0.59	11.82	1.90	2.98	13.88	455.50	26.20	32.82	28.33
Ostrówek P.II	0-50	4.61	3.03	4.37	0.41	0.54	0.28	3.77	0.17	1.88	10.27	459.63	65.83	44.75	25.05
Jelino I	0-80	4.67	3.35	5.83	0.44	1.46	1.42	6.37	0.60	0.46	11.33	353.25	121.58	31.18	25.75
Jelino II	10-50	3.62	2.89	4.30	0.11	0.30	0.83	2.25	0.24	0.53	13.80	410.00	6.69	29.71	125.45
Podlaski I	0-80	4.32	3.18	2.27	0.40	0.90	1.12	1.82	0.19	2.29	12.95	559.65	38.00	43.22	32.38
Podlaski II	0-10	5.17	3.65	1.90	0.51	1.05	1.35	7.34	0.36	3.51	15.00	475.30	24.90	31.69	29.41
Krasne I	0-50	4.36	3.25	9.97	0.43	0.83	0.71	7.56	0.44	7.42	16.70	523.00	124.27	31.32	38.84
Krasne II	0-50	4.12	3.11	6.58	0.30	0.24	0.33	15.80	0.92	0.78	10.10	464.98	13.20	46.04	33.67
Stulno I	0-80	4.40	2.17	3.17	0.31	0.66	0.36	1.74	0.48	2.57	7.73	479.23	12.33	62.00	24.94
Stulno II	0-80	4.40	2.34	3.30	0.13	0.34	0.77	1.89	0.39	0.26	8.02	478.3	59.6	59.64	61.69
Macoszyn I	15-50	4.40	2.50	3.25	0.68	0.55	0.79	1.64	0.45	0.87	8.60	266.05	32.60	30.94	12.65
Raised pine peat															
Ostrówek P.I	30-60	4.02	2.87	11.70	0.20	0.22	0.65	7.25	0.32	1.06	17.05	527.95	7.97	30.96	85.25
Raised cotton grass - *Sphagnum* peat															
Ostrówek P.I	60-80	4.40	2.96	4.30	0.31	0.20	0.08	3.11	0.10	4.66	14.00	369.70	73.20	26.41	45.16
Macoszyn I	0-15	4.56	2.50	3.10	0.65	1.69	1.26	3.38	0.20	0.53	8.00	361.60	229.50	45.20	12.31
Osowa II	0-40	3.81	–	9.93	0.30	0.45	0.43	4.50	0.29	0.92	13.80	459.08	21.80	33.27	46.00

Table 3. Continuation

Study object	Depth (cm)	pH H$_2$O	pH KCl	Ash content (%)	P	K	Na	Ca	Mg	Fe	N	C	Mn (mg kg^{-1})	C/N	N/P
					(g kg^{-1})										
Low moor sedge peat															
Albertów II	340-350	5.73	4.53	15.60	0.29	0.20	0.44	8.07	1.10	0.82	37.60	505.70	7.32	13.45	129.66
Ostrówek P.I	80-160	4.52	3.36	24.23	0.15	0.23	0.85	8.72	0.43	1.46	19.53	561.07	9.08	28.73	130.20
Ostrówek P.I	200-250	4.71	4.07	35.70	0.24	0.63	0.36	3.43	0.79	8.19	18.50	472.70	20.00	25.55	77.08
Jelino I	170-210	4.55	3.94	44.10	0.50	7.01	1.48	2.76	1.37	14.00	7.70	224.07	53.70	29.10	15.40
Jelino II	80-180	4.37	3.39	5.57	0.11	0.44	0.73	3.16	0.43	0.63	18.33	582.60	9.32	31.78	166.64
Podlaski II	10-30	4.32	3.28	2.50	0.40	0.67	0.75	4.86	0.35	8.64	13.15	437.45	55.40	33.27	32.88
Krasne I	60-130	4.46	3.70	10.50	0.32	0.44	0.20	3.56	0.89	0.47	18.00	577.00	18.80	32.06	56.25
Krasne II	100-110	4.96	3.73	10.50	0.32	0.24	0.20	3.36	0.79	0.47	16.50	576.00	18.80	34.91	51.56
Osowa I	150-300	4.55	–	17.32	0.23	0.83	0.46	9.7	0.41	2.89	23.6	81.35	18.2	3.45	102.61
Osowa II	150-260	4.01	–	13.04	0.16	0.62	0.38	12.47	0.32	3.2	17.7	546.2	13.72	30.86	110.63
Low moor *Hypnum*-moss peat															
Ostrówek P. I	160-200	4.94	3.82	22.70	0.04	3.21	1.07	6.03	1.72	0.50	13.40	557.70	44.50	41.62	335.00
Ostrówek P. II	170-190	5.01	4.03	16.70	0.61	0.53	0.29	7.98	0.08	1.43	11.50	502.40	27.70	43.69	18.85
Jelino II	180-210	4.63	3.74	4.50	0.11	0.80	0.55	4.20	0.70	1.32	14.10	129.80	15.40	9.21	128.18
Podlaski I	130-170	4.64	3.78	6.30	0.33	1.67	1.44	2.28	0.34	2.67	17.15	587.05	25.00	34.23	51.97
Stulno I	200-250	4.98	3.75	3.42	0.48	0.59	0.21	6.00	0.33	1.58	7.32	532.95	17.17	72.81	15.25
Stulno II	200-240	4.49	3.72	3.40	0.13	0.55	0.55	1.53	0.25	0.84	18.75	439.30	9.44	23.43	144.23
Macoszyn II	90-110	3.89	3.33	6.34	0.36	0.41	0.56	1.02	0.21	0.58	10.80	351.20	11.80	32.52	30.00
Detrital (organic) gytt															
Albertów I	70-130	4.20	3.08	10.05	0.43	0.28	0.34	8.19	1.21	1.16	22.65	467.00	11.00	20.62	52.67
Albertów II	100-300	4.49	3.48	11.20	0.36	0.28	0.35	8.11	1.30	0.88	30.60	477.00	8.00	15.59	85.00
OstrówekP.II	50-170	4.72	3.77	16.25	0.23	0.18	0.14	16.70	0.35	0.90	15.60	563.25	22.60	36.11	67.83
Krasne I	130-150	4.23	3.24	11.00	0.27	0.19	0.62	2.58	0.37	1.96	23.80	627.80	17.60	26.38	88.15
Stulno I	100-200	4.38	3.20	13.81	0.46	0.78	0.36	1.66	0.81	2.29	17.81	510.69	16.6	28.67	38.72
Stulno II	100-200	4.46	3.60	10.47	0.13	0.61	0.55	3.01	0.41	0.58	12.37	462.72	18.01	37.41	95.15
Macoszyn I	90-130	4.66	3.64	14.54	0.47	0.67	0.74	2.71	0.83	1.36	9.10	310.40	26.65	34.11	19.36
Macoszyn II	110-120	4.99	4.13	15.30	0.36	0.41	0.56	1.55	0.40	0.95	14.40	351.20	11.80	24.39	40.00
Mursh															
Ostrówek P. I	0-30	3.85	2.74	9.63	0.63	0.42	0.73	9.50	0.63	3.15	18.63	124.83	21.03	6.70	29.57
Jelino II	0-10	3.50	2.74	11.00	0.62	0.48	0.92	2.01	0.19	1.13	13.50	110.20	12.00	8.16	21.77

Table 4. Relationships between the parameters measured in peat

Parameter	pH in H_2O	pH in KCl	P	N	Ca	Mg	K	Na	Fe	Mn	C	Ash content
pH in H_2O		–	-0.21*	0.48**	–	–	-0.34*	-0.43**	0.14*	–	–	–
pH in KCl			-0.34**	-0.44**	–	–	-0.31*	-0.41*	0.36**	–	–	–
P				-0.36**	-0.47***	-0.27*	–	0.48*	–	0.51**	–	-0.21*
N					0.25*	–	0.37*	-0.33**	0.47*	–	0.44**	0.23*
Ca						–	–	-0.30*	–	–	–	–
Mg							–	–	–	–	0.24*	–
K								–	0.31*	0.32**	0.4**	0.21*
Na									–	0.33*	–	–
Fe										–	0.27*	–
Mn											–	–
C												0.49**

n = 481, linear, R – coefficient, $^*p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$.

Leifeld *et al*., 2011) and assessing the extent of peatland degradation. The more natural and intact a peatland area is, the greater the preponderance of carbon accumulation over carbon oxidation. Drainage, as well as agricultural and mining activities result in the release of carbon in the form of CO_2, which leads to the subsidence and compaction of peat and, consequently, to the enrichment of the surface layer with mineral matter. The ash content is also an indicator of peat decomposition (Clymo, 1984). Based on the results obtained in the present study, it can be said that the bottom layer of gyttja contains the largest amounts of mineral matter compared to the other layers. The high content of ashes is due to the presence of clay deposits in this layer, and its enrichment with nitrogen, calcium and iron. The peat deposits, on the other hand, are characterized by a low ash content (below 20%), a property that is associated with a high content of carbon, mainly organic, which is sequestered in the peat mass. Transitional peat, because of its composition and the properties of the organic matter it is formed from, contains over 45% of carbon and, thus, has the lowest ash content (5.5%). Studies conducted in Central Europe have shown that the ash content also increases as a result of increased contents of pine and spruce in the peat mass (Görres and Bludau, 1992). Investigations carried out in Southern Poland have not confirmed that there is a clear relationship between the botanical type of peat and its ash content. However, these studies established the following sequence of a decreasing ash content: gyttja > *Alnioni* peat> *Magnocaricioni* peat > *Bryalo-Parvocaricion* peat > *Ombro-Sphagnioni* peat (Malawska *et al*., 2006). Similar results have been obtained for deposits from the peatlands of North-Eastern Poland (Twardowska *et al*., 1999). Compared to peat layers, moorsh contains the lowest amounts of carbon, which is due to a change in the water-air conditions and the mineralization processes which lead to the release of CO_2 into the atmosphere and, ultimately, to the compaction of organic matter.

The organic content is considered to be the main parameter that decides about the physical and chemical properties of peat (Rydelek, 2013). The highest contents of biogenic elements (phosphorus and nitrogen) in the investigated peatlands were found in their uppermost layers, which are connected with the accumulation of plant remains, the decomposition of peat soils and the supply of phosphorus compounds as a result of fertilization and erosion. On the other hand, a stronger decomposition of organic matter promotes a decrease in the phosphorus content in the underlying layers of clayey gyttja (Sapek and Sapek, 1993). The high chemical affinity of phosphorus and organic matter, and the resulting ability of this element to be sorbed by peat materials, on the one hand, and the possibility of generating active compounds of phosphorus with soluble organic carbon and other mineral components, on the other, mean that the complex process of phosphorus transfer to bodies of water requires continuous monitoring due to the eutrophic potential of this component.

Low moor peats are characterized by higher nitrogen contents than transitional peats. A similar observation was made by Ringqvist and Öborn (2002) who found that peats feature a large diversity of nitrogen compounds (humic, amine, and unidentified forms, amino acids, *etc*.) (Kunnas and Eronen, 1994). The main sources of nitrogen are plant remains, root secretions and precipitation. Nitrogen compounds in peats are subjected to humification and mineralization, in the course of which organic forms are transformed into mineral ones, and *vice versa* (Ilnicki, 2002). The mineralization of nitrogen compounds depends indirectly on the degree of peat decomposition, which directly affects the air-water conditions, which in turn determine the rate and extent of mineralization. Wassen and Venterink (2006) have shown that the Biebrza peat bogs have a significant positive nitrogen balance, indicating the abundance of this element for vegetation. These authors believe that the positive nitrogen balance in these peat bogs is caused by a low nitrogen mineralization rate, which is a consequence of lower fluctuations in the water level in the summer months.

An important indicator of the availability of nitrogen released in the process of degradation of plant remains contained in peats is the C:N ratio (Anderson, 2002; Malinowski *et al*., 2016). Factors that can influence this parameter include the nitrogen content in the deposit, temperature, the moisture content, the soil pH and oxygen conditions. The C:N ratio also provides information on the degree of decomposition. According to Heathwaite and Göttlich (1993), a low C:N ratio indicates a high degree of decomposition, and vice versa. The lowest C:N ratio was observed for moorsh (6.9-8.16), which was characterized by the highest degree of decomposition, an observation that confirms Heathwait and Götlich's findings (1993). The C:N ratio in transitional and low moor peats exceeded 30, indicating a reduction in the mineralization rate, as well as the fact that soil microorganisms took up nitrogen assimilable by plants. The C:N ratio in moorsh (Ostrówek Podyski and Jelino) indicates that the nitrogen released by microorganisms from plant remains is not fully utilized by plants, as previously pointed out by Lucas (1982). Rydin and Jeglum (2006) observed a very wide range of C:N ratios in the top layers of peat deposits, which was due to a stronger decomposition of plants and the release of nitrogen. As the depth of the profile increases, a reverse process starts to be observed. Soil microorganisms slowly consume carbon and recirculate nitrogen, leading to a gradual decrease in the C:N ratio. In addition, low temperatures slow down the decomposition of organic matter by slowing down the activity of microorganisms, resulting in a further decrease in the C:N ratio. Our research confirms the results obtained by Rydin and Jeglum (2006). We noted a similar trend, with the highest C:N ratio observed in the uppermost layer of the profiles (C:N = 58 in the 0-40 cm layer), and the ratio decreasing with the increase in depth (*e.g.* at the depth of 340-350 cm, C:N = 13.50).

The availability of nitrogen and phosphorus is a growth-limiting factor for most plants. The N:P ratio is used to describe which of the two biogens limits plant growth, but the optimum N:P ratio depends on the species, growth rate and age of plants. It has also been observed that high N:P ratios promote the growth of grasses (graminoids) and stress-tolerant plants (*e.g.* peatland plants) (Güsewell 2004). Bedford *et al*. (1999) observed that the N:P ratio in the top profile layers was lower in marshes and swamps than in bogs and fens. In addition, the N:P ratio increased rapidly when the organic matter content was above 90%. Wassen *et al*. (2005) pointed out that an N:P ratio of less than 13.5 denoted N-limitation, a ratio between 13.5 and 16 meant that both biogens were limited, and an N:P ratio above 16 indicated P-limitation. In our study, a limiting impact of phosphorus on the growth and development of vegetation was observed for all the deposit types.

Calcium is taken up by plants in large quantities, so it is relatively quickly depleted from the environment. Even with the apparent abundance of calcium compounds, its uptake by plants may be significantly inhibited, as is the case with highly acidified peat. Calcium uptake by plants depends on both the pH of the habitat and the organic matter content.

The magnesium content increased with an increasing organic matter content, which is why the moorsh layers contained lower amounts of this element compared with peat layers, pointing to a high mobility of this component in the environment.

As a monovalent cation, potassium exhibits high mobility in the environments rich in organic matter. The low content of potassium in the samples collected in the study confirms the literature data and clearly indicates that peat soils do not accumulate this element, as opposed to mineral soils, especially clayey ones (Łachacz, 1998).

CONCLUSIONS

1. There were differences in chemical properties between the analyzed peat deposits. The highest ash content was displayed by the low moor Sedge peat, while the smallest by the transitional Sedge-Sphagnum peat. As a rule, the lowest concentrations of the analyzed parameters occurred in the raised pine peat (Mn, Fe, K, P), while the highest were very diverse in individual botanical types of peatlands.
2. In all the studied deposits, the carbon content was high, especially in the transitional sedge – *Sphagnum* peat and the raised pine peat. The moorsh layers, in relation to the studied peat minerals and gyttja, were characterized by lower carbon content and the restriction of C:N and N:P ratios.
3. In all the studied peat bogs, located in the Łęczna-Włodawa Plain, the accumulation phase dominated, so they do not act as carbon suppliers.

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