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ORIGINAL PAPER

Effect of TOC and depth on soil chemical properties and labile carbon pool in the topsoil of drained peatlands*

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Abstract

The differentiation of soil parameters is most frequently studied between soil horizons. However, in drained organic soils, the mursh-forming process changes peat into mursh in the topsoil, the layers of which may behave differently. The aim of the study was to characterize how soil chemical properties and the labile carbon pool respond to the mursh-forming process at three depths: 0-10 cm, 10-20 cm and 20-30 cm, as well as at various TOC levels. Secondly, we attempted to answer the question whether different labile carbon fractions display the same response and can be regarded as indicators of the changes in mursh. In the study, we determined the following soil properties: organic matter, carbon, nitrogen contents, hot and cold water-extractable carbon (HWC and CWC), calcium chloride extractable carbon ($CaCl_2$-C), soil sorption properties, and bioavailable forms of Fe, Mn, K, Ca, Mg, Zn, Cu. The results of the study revealed that the determined soil properties were changing along with the depth, and were also dependent on the total organic carbon content. Most of decomposable and mineralizable organic matter occurred in the 10-20 cm or 20-30 cm layers, especially when HWC or $CaCl_2$-C were taken into account. The variability of the results among the studied depths was explained in a PCA analysis by organic matter and carbon content as well as soil sorption properties, Zn content and labile carbon fractions contents, mainly HWC. The study revealed that HWC is an excellent indicator of changes occurring under the mursh-forming process, whereas CWC proved to be ineffective as an indicator.

Keywords: CWC, drainage, HWC, mursh, soil sorption properties

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INTRODUCTION

Globally, the carbon stored in soils exceeds the amount of carbon in the vegetation and atmospheric pools (Scharlemann et al. 2014). A third of global soil carbon is stored in peatlands (Page and Baird 2016) although they cover only 3% of the Earth's surface (Chimner et al. 2017). Organic carbon in peatlands is accumulated in anaerobic and water-saturated conditions. Natural water-saturated peatlands sequestrate carbon in peat vegetation. When a peatland is drained, the stored carbon is released to the atmosphere as CO_2 (Fell et al. 2016, Kasimir et al. 2018). Generally, soil organic carbon comprises active, labile, inactive and stable pools, and is considered as a crucial indicator of soil quality (Ramesh et al. 2019). The most active pool of SOC is labile carbon, which includes dissolved organic carbon (DOC), hot and cold water-extractable organic carbon (HWC and CWC), calcium carbonate extractable organic carbon ($CaCl_2$-C) or easily oxidizable organic carbon (Chen et al. 2016, de Souza et al. 2016, Glina et al. 2022, Kalisz, Lachacz 2023). In contrast, recalcitrant organic carbon and mineral-associated organic carbon create stable pools (Smólczynski et al. 2011, Kalisz et al. 2021).

Labile organic carbon fractions in soils are considered to be primary and sensitive indicators of soil quality and organic matter changes (carbon cycling) because they have a short-term turnover and are biologically active (Sa et al. 2018, Zhou et al. 2023), being a readily usable energy source for microorganisms (Zhang et al. 2021). The soil labile organic carbon pool is composed of amino-acids, carbohydrates, microbial biomass and other simple organic compounds (Zou et al. 2018). One of the labile carbon components is HWC, which is correlated with the mass of microorganisms and simultaneously is an excellent indicator of qualitative changes in organic matter (Sparling et al. 2016, Kalisz et al. 2021, Smolczynski et al. 2021, Glina et al. 2022, Mencel et al. 2022). HWC is the carbon fraction most susceptible to oxidation to CO_2 (Cao et al. 2017). It represents a small but significant fraction of the SOC with high reactivity (McKee et al. 2016), being a source of nutrients and energy for microorganisms. Another common labile fraction of organic carbon in soils is CWC. Quantitatively, it is similar to dissolved organic carbon, which is frequently measured directly in soil with a lysimeter (Irvine et al. 2021), and has lower biodegradability rates than HWC (Gregorich et al. 2000). Soil carbon extracted with neutral salt solutions, such as calcium chloride ($CaCl_2$), may also be a good indicator of changes in organic matter, although it has not been widely used in studies on organic soils (Łachacz, Kalisz 2011).

Organic peat soils are vulnerable to changes induced by drainage (Oleszczuk et al. 2013, Hewelke et al. 2016, Oleszczuk et al. 2022), which initiates a series of transformations of peat (the mursh-forming process), i.e. the release of organic compounds and nutrient leaching (Klove et al. 2010, Pham et al. 2023) through the oxidation of the upper most layers of peatland (Kalisz et al. 2010, Kalisz et al. 2015, Renou-Wilson et al. 2019, Kalisz et al. 2021, Smolczynski et al. 2021, Kalisz, Lachacz 2023, Lachacz et al. 2023, Seidel et al. 2023). Any alteration of a peatland ecosystem, especially drainage, leads to changes in organic carbon pools (Lohila et al. 2011, Renou-Wilson et al. 2014, Norberg et al. 2018, Glina et al. 2022, Kalisz, Lachacz 2023), and consequently in the elemental composition. It is well known that the mursh-forming process changes the chemical status of organic soils, an alteration that is either related to the content of organic matter and organic carbon concentrations or the vertical position in a soil profile (Piaścik, Łachacz 2001, Kalisz, Łachacz 2009, Smólczyński, Orzechowski 2010*a*,*b*, Smólczynski et al. 2015, Smolczynski et al. 2021). However, little is known about the effects of TOC contents and depth on the labile carbon pool in the topsoil of drained peatlands. The differentiation of soil parameters is most frequently studied between soil horizons. However, in drained organic soils, the mursh-forming process changes peat into mursh in the topsoil and further, when the process is advanced, mursh may be transformed into the humus mineral topsoil. Therefore, changes occurring in the topsoil are of great importance, especially in drained Histosols. Okruszko and Ilnicki (2002) described the morphology of a mursh soil profile, distinguishing three layers in the mursh horizon. These three layers differed in the structure and advancement of the mursh-forming process (Łachacz et al. 2023). The topsoil of drained peatland is not homogenous, and so the soil properties may not be similar. The aim of the study was to characterize how soil chemical properties (soil sorption properties and contents of selected elements) and labile carbon pool respond to the mursh-forming process at three depths in the topsoil: 0-10 cm, 10-20 cm and 20-30 cm, as well as at various TOC levels. Secondly, we attempted to answer the question whether different labile carbon fractions display the same response and can be regarded as indicators of the changes in the topsoil.

MATERIALS AND METHODS

The studied soils are located in north-eastern Poland, in the Mazurian Lakeland region (Figure 1), where the climate is moderate continental-maritime, with average annual air temperature of about 7.5-8.0°C, and average annual rainfall from 550 to 650 mm. The studied peatlands had been drained for agricultural purposes in 19th and 20th century, and used as grasslands (meadows). At each site, soil samples (n=30) were taken from three layers: 0-10 cm (S1), 10-20 cm (S2) and 20-30 cm (S3). The soils under study were classified as Murshic Hemic Histosols (IUSS 2022) and as hemic murshic soils (Polish Soil Classification, Kabala et al. 2019).

Site A (6 soil samples) represents a peatland that had been formed from moderately decomposed sedge and rush peats underlain by clay or calcareous

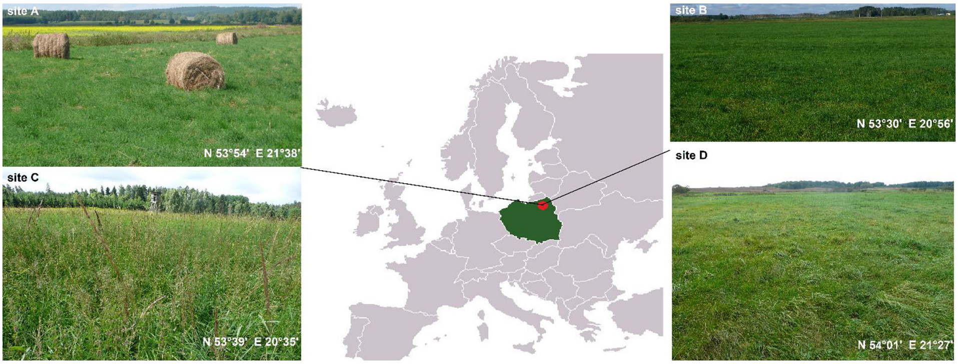

Fig. 1. Location of studied peatlands and the state of their management

gyttja. It was drained in the second half of the nineteenth century, later re-wetted and drained again. The organic matter contents of mursh soils which developed at this site depended on management practices (periods of grassland or ploughland uses) causing mineralization.

Site B (6 soil samples) represents a peatland that had been formed from moderately decomposed rush and moss peats underlain by calcareous gyttja. It was drained at the beginning of 20th century, and mursh soils developed. The amount of organic carbon in mursh soils is a derivative of the mineralization of organic matter caused by drainage and grassland use.

Site C (12 soil samples) represents a peatland that had been formed from moderately decomposed rush and moss peats underlain by clay-calcareous gyttja. It was drained at the beginning of 20th century, and mursh soils developed. It has been re-wetted and drained several times since then. The amount of organic carbon in mursh soils is a derivative of the mineralization of organic matter caused by drainage and grassland use as well as the sedimentation of sand from adjacent uplands.

At site D (6 soil samples), the peatland had been formed from moderately decomposed sedge and rush peats underlain by detritus-calcareous gyttja. It was drained in the second half of the nineteenth century, and mursh soils developed. The amount of organic carbon in mursh soils is a derivative of the mineralization of organic matter caused by drainage and grassland use (with periods of ploughland use) and the sedimentation of mineral matter from the Guber River floods.

Soil samples were air-dried and visible plant remains were removed manually. For laboratory analysis, soil samples were ground to pass through a 1.0 mm sieve. Loss-on-ignition (LOI), an approximate measure of organic matter (OM), was determined after dry ashing of soil samples for 6 h at a temp. of 550°C. Total organic carbon (TOC) and total nitrogen (TN) were measured on a Vario MaxCube Elementar analyser. In order to demonstrate the differences between the studied soil parameters, the soil samples were divided into two groups on the basis of the TOC content: A – a group of samples with TOC < 30%, and B – a group of samples with TOC > 30%.

Soil reaction was determined potentiometrically in 1 M KCl. The basic exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were extracted with 1.0 M ammonium acetate, and measured on an iCAP Duo 7400 ICP-OES spectrometer (Thermo Scientific). By summing up the content of basic cations, sum of base cations (SBC) was calculated. Exchangeable hydrogen (H^+) was determined in barium chloride and triethanolamine buffer solution $BaCl_2$-TEA (van Reeuwijk 2002). Cation exchange capacity (CEC) was calculated as the sum of SBC and H^+. The potentially bioavailable forms of macro- and microelements (Ca, Fe, Mn, Mg, K, Zn, Cu) were extracted with 0.5 M HCl according to Sapek (Sapek et al. 2009) and measured on an iCAP Duo 7400 ICP-OES spectrometer (Thermo Scientific).

The hot-water extractable C was determined in air-dried soil samples. Briefly, 4 g of air-dried soil was incubated with 20 ml demineralized water in a capped test-tube at 70°C for 18 h. The tubes were shaken by hand at the end of incubation and then filtered through Whatman ME 25/21 ST 0.45 μm membrane filters (mixed cellulose ester) (Sparling et al. 1998). Cold water extractable carbon (CWC) was determined in air-dried soil samples. CWC extracts were obtained by shaking 10 g aliquot of soil sample with 10 ml deionized water horizontally at 180 rev min^{-1} for 24 h (Landgraf et al. 2006). Then, the suspension was centrifuged at 4000 rev min^{-1} for 10 min and decanted. Calcium chloride-extractable C was determined in air dried samples. The extraction was performed for 2 h with a 0.01 M $CaCl_2$ dm^{-3} at 20°C in a 1:10 extraction ratio (weight of soil/volume of extractant). Then, the soil solution was filtrated (Houba et al. 2000). All analyses were carried out in triplicate. The concentration of organic carbon was measured on a Multi N/C 3100 Analityk Jena analyser.

The statistical analyses were performed using Statistica 13. Most of the studied parameters were not normally distributed (determined by the Shapiro-Wilk test). The relationships between soil parameters and soil carbon pools were analysed using ANOVA and Principal Component Analysis (PCA). Pearson's correlations were used to determine the correlation coefficients between variables.

RESULTS AND DISCUSSION

Organic carbon contents

The studied surface horizons (topsoil) of drained peatlands contained an average of 674.3 g kg^{-1} of organic matter, 370 g kg^{-1} of organic carbon and 25.31 g kg^{-1} of total nitrogen (Table 1). The C/N ratio of the studied layers amounted to 16.48 on average (Table 1), which is typical for drained organic soils. These values are not low with respect to drained peatlands. The pH values of the studied formations were not highly varied and ranged

Table 1

Overview of the soil properties for the studied peatlands' mursh horizons

Variable	Minimum	Maximum	Mean	SD
OM (g kg^{-1})	147.5	892.5	674.3	190.0
TOC (g kg^{-1})	82.64	506.9	370.1	104.7
TN (g kg^{-1})	22.83	27.53	25.31	2.091
C/N	12.33	21.97	16.48	3.764
$CaCl_2$-C (g kg^{-1})	5.396	12.55	8.810	1.870
HWC (g kg^{-1})	1.472	6.072	3.991	1.233
CWC (g kg^{-1})	0.204	2.571	0.907	0.492

SD – standard deviation

from 4.7 to 6.2, that is acidic or slightly acidic reaction. The content of labile organic carbon fractions in the studied layers ranged from 0.204 g kg^{-1} (CWC fraction) to 12.55 g kg^{-1} ($CaCl_2$-C fraction). More carbon was extracted using $CaCl_2$ (mean 8.81 g kg^{-1}), less using hot water (mean 3.99 g kg^{-1}), and the least (< 1 g kg^{-1}) using cold water (Table 1). Labile carbon therefore constituted a small share in total organic carbon, up to 7% and approximately 1-2% on average. These values are typical for drained fens (Glina et al. 2012, Kalisz et al. 2015, Glina et al. 2022, Kalisz, Lachacz 2023).

The content of the studied labile carbon fractions differed depending on the depth (S1-S3) and the TOC content (A and B) in a given layer, as shown in Figure 2. The differences were distinct for $CaCl_2$-C and HWC fractions in soil layers containing < 30% TOC (group A). The contents of HWC and $CaCl_2$-C fractions in group A were the highest in S2 (mean: 9.42 g kg^{-1} $CaCl_2$-C and 4.078 g kg^{-1} HWC), and lower in S1 and S3 layers. Whereas in group B, they were increasing with depth (Figure 2). In turn, the contents of CWC fraction were relatively similar in group A, and greater fluctuations in the CWC content occurred in group B. The CWC fraction in group A showed the lowest values in the 10-20 cm layer (0.653 g kg^{-1}) – contrary to HWC and $CaCl_2$-C, while in group B the highest values (mean: 1.263 g kg^{-1}) were determined at the 10-20 cm depth (S2).

The results of the present study suggest that most decomposable and mineralizable organic matter occurs in the 10-20 cm or 20-30 cm layers, especially when HWC or $CaCl_2$-C are taken into account. The HWC fraction contains microbial biomass, soluble forms of some organic compounds, including humus (Ghani et al. 2003, 2013) and components that form a reserve of nutrients and energy for plants and microorganisms. Its amount also provides information on the soil C and N that can be mineralized (Wei et al. 2024). The $CaCl_2$-C fraction is also regarded as highly biodegradable and the one which contains most mobile soil compounds (Houba et al. 2000), therefore it is also regarded as a reserve of nutrients for microbes. The contents of these two fractions (HWC and $CaCl_2$-C) suggest that the energy and

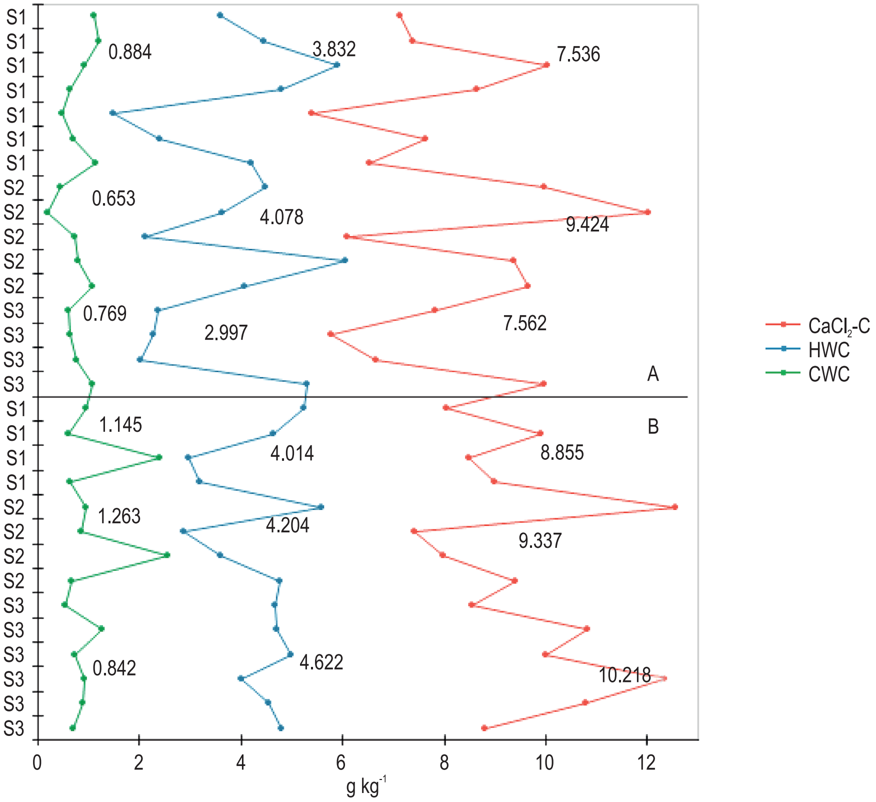

Fig. 2. Amounts of labile carbon fractions: A – group of samples with TOC < 30%, B – group of samples with TOC > 30%, S1, S2, S3 are the sampled depths: 0-10 cm, 10-20 cm and 20-30 cm, respectively

nutrients for microbial transformations are mostly present in the S2 and S3 layers, therefore these two carbon fractions are higher in content there. However, the CWC fraction is considered to affect the transport of nutrients (Gregorich et al. 2000), but its distribution does not seem to have the regularity that can be related to microbial activity.

Soil sorption properties

Calcium cations outnumber all other cations present in the soil sorption complex in all the soil layers (Table 2, Figure 3). Its highest values were determined in the 20-30 cm soil layer, and lower amounts appeared in the upper layers (Table 2), which is typical for drained lowland peatlands and is attributed to the leaching of Ca (Kalisz, Łachacz 2009, Lachacz et al. 2023). The concentration of Ca^{2+} was also related to the TOC amount, and it oscillated around 620 and 630 mmol(+) kg^{-1} in the layers with TOC lower than 30% (group A), whereas in the layers having more TOC, the concentration

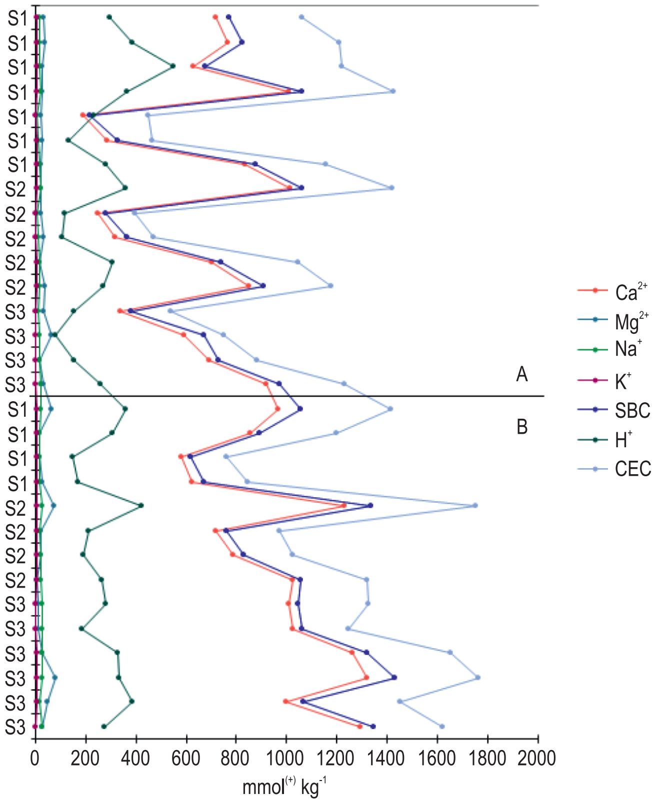

Fig. 3. The content of cations in the soil sorption complex: A – group of samples with TOC < 30%, B – group of samples with TOC > 30%, S1, S2, S3 are the sampled depths: 0-10 cm, 10-20 cm and 20-30 cm, respectively

Table 2

Exchangeable cations at the studied depths of the topsoil of drained peatlands (mean ± SD)

Name*	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SBC	H^{+}	CEC
	mmol(+) kg^{-1}						
S1_A	633.8±294.8	27.6±6.1	14.5±5.6	3.62±1.16	679.4±302.6	319.3±130.8	998.8±385.9
S2_A	627.3±332.5	26.1±9.1	14.7±6.1	2.77±0.96	670.9±338.5	230.5±114.4	901.4±448.8
S3_A	634.6±239.3	35.5±20.1	15.7±4.6	2.28±0.45	688.0±242.4	162.6±74.0	850.6±291.0
S1_B	757.1±185.3	29.9±22.2	17.8±3.3	4.33±0.12	809.1±203.7	246.3±104.0	1055.4±307.3
S2_B	940.6±234.1	29.8±29.3	21.1±3.0	3.45±0.40	995.0±258.6	273.1±103.9	1268.0±359.7
S3_B	1152.0±155.7	32.5±26.5	25.1±3.9	2.92±0.21	1212.5±172.5	298.1±69.2	1510.6±202.0

* S1, S2, S3 – are the sampled depths: 0-10 cm, 10-20 cm and 20-30 cm, respectively: A – group of samples with TOC < 30%, B – group of samples with TOC > 30%

of Ca^{2+} was higher (Table 2). The second dominant cation was magnesium, for which the highest contents were also determined in the 20-30 cm layer (Table 2). It is also typical that the content of magnesium in organic soils is several times (or even more) lower than that of Ca, and has a similar tendency for leaching (Lachacz et al. 2023, 2024).

The sodium cations were less numerous (Table 2, Figure 3) in the soil sorption complex, and showed similar distribution to Ca^{2+} at the studied depths. The content of potassium cations was the lower, and its distribution was contrary to that of calcium or sodium cations. However, according to Okruszko (1993), the process of mursh formation after drainage does not significantly affect the distribution of potassium in the soil profile. Exchangeable hydrogen showed the highest concentration in the uppermost layer, and occurred in lower amounts in the 10-20 cm and 20-30 cm layers (Table 2). The calcium leached from the surface layers is replaced with H^+, thereby contributing to further soil acidification.

The sum of base cations (SBC), owing to calcium, sodium and magnesium cations, was also increasing with the depth of the layers analysed (Table 2, Figure 3). The values of CEC, which are the derivatives of SBC and H^+, were the highest in the 20-30 cm layer, and lower in upper layers. The amount of TOC also influenced CEC values, which were higher in soils with higher TOC values (group B; Table 2, Figure 3). The average CEC of mursh in the soil profile is typically lower than in underlying peats (Piaścik Łachacz 2001), and also lower in the uppermost surface layers. The above relationships between cations, including calculated SBC and CEC values, confirm the conclusions drawn in other studies, namely that Ca^{2+} is forced out by H^+ in the sorption complex during mursh formation, and also leached down the soil profile, consequently the Ca concentration decreases, which is referred to as soil decalcitation (Okruszko 1993, Lachacz et al. 2023). The acidification of the surface layers may in turn influence the microbial activity (Horn et al. 2021), and therefore can also affect the content of labile carbon fractions in the topsoil of peatlands.

Content of selected macro- and microelements

The iron content was the highest in the surface layers of group A soil formations (mean 46.8 g kg^{-1}) – Table 3, Figure 4, which may indicate the ongoing pedogenetic processes, and this element accumulates in the surface layers of the soil as a result of the mursh-forming process. The content of iron was not increasing with depth, and its amounts were not always higher in the uppermost layers. Generally, iron comes from the decomposition of plant residues present in peat or water rising from deeper layers. Its content is also the result of alluvial and deluvial processes (Smolczynski et al. 2011). Iron released to the environment occurs in various forms, and it is chemically and microbiologically transformed, especially in soils rich in organic matter.

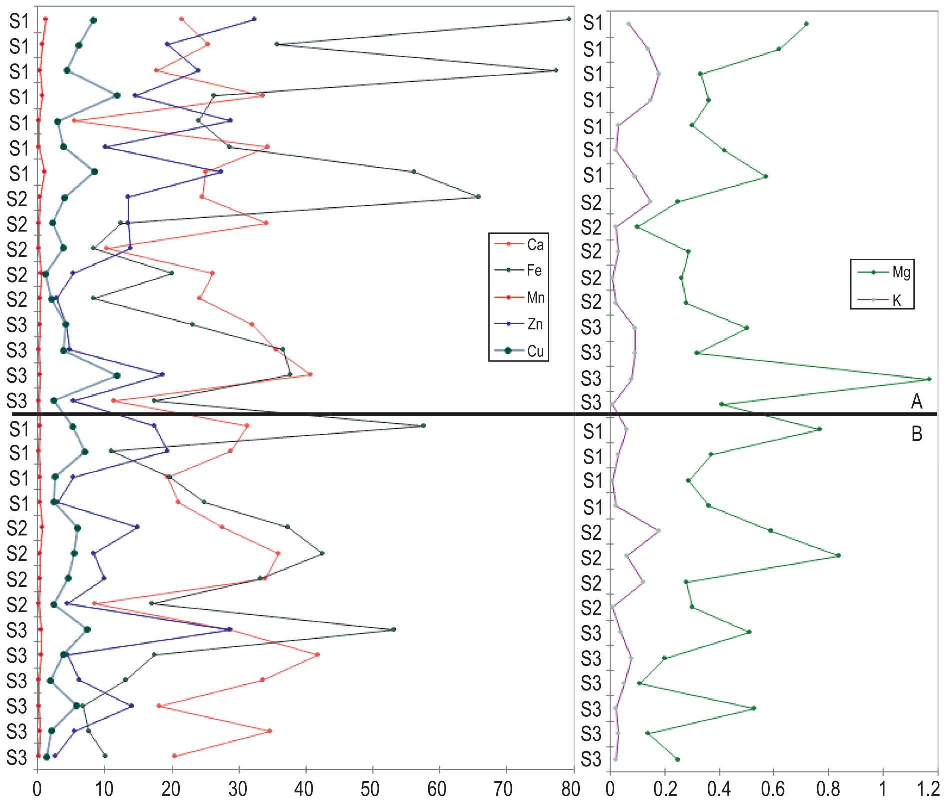

Fig. 4. The content of macro- and microelements (Ca, Fe, Mn, Mg, K in g kg^{-1}; Cu, Zn in mg kg^{-1}) in studied layers: A – group of samples with TOC < 30%, B – group of samples with TOC > 30%, S1, S2, S3 – are the sampled depths: 0-10 cm, 10-20 cm and 20-30 cm, respectively

Table 3

The content of macro- and microelements at the depths of the topsoil of drained peatlands (extracted with 0.5 M HCl, mean ± SD)

Name*	Ca	Fe	Mn	Mg	K	Zn	Cu
	(g kg^{-1})					(mg kg^{-1})	
S1_A	23.30±9.918	46.80±24.10	0.584±0.415	0.474±0.162	0.097±0.061	22.34±8.064	6.517±3.121
S2_A	23.86±8.618	22.99±24.45	0.243±0.114	0.236±0.078	0.046±0.058	9.802±5.326	2.642±1.240
S3_A	29.87±12.86	28.71±10.04	0.226±0.100	0.600±0.387	0.067±0.039	8.252±6.969	5.542±4.278
S1_B	25.11±5.886	28.29±20.39	0.285±0.077	0.447±0.218	0.030±0.022	11.26±8.321	4.300±2.196
S2_B	26.46±12.54	32.57±11.02	0.380±0.206	0.502±0.266	0.092±0.074	9.430±4.280	4.592±1.541
S3_B	29.59±9.051	18.06±17.62	0.293±0.172	0.290±0.185	0.040±0.023	10.22±9.866	3.696±2.409

* as in Table 2

The content of calcium was also very high in the soils, and was changing with the depths studied (Table 3, Figure 4). It was the lowest in surface layers (mean 23.1-25.3 g kg^{-1}) and the highest in the 20-30 cm layer (mean 29.59-29.87 g kg^{-1}). Such a pattern is typical for drained peatlands, and it is related to the leaching of calcium (decalcification), as has already been mentioned above. The content of magnesium was dozen times lower than that of calcium (Table 3, Figure 4), which is typical for organic soils. For magnesium, no regularity in the distribution was found. The manganese content in the soils was also varied, and its highest values were found in the upper layers with a lower content of TOC (group A) – Table 3, Figure 4. This may suggest the current and former redox conditions of the soil; besides, manganese can form permanent bonds with organic substances. The potassium content was low, with no regularity among the studied layers, which is also typical for organic formations, and confirms the assertion of Okruszko (1993) that this element occurs independently of the depth. Similarly to Mn, the contents of zinc and copper were the highest in the upper layers with a lower content of TOC (group A) (Table 3, Figure 4). However, the content of Zn was decreasing along with the depth in the topsoil (Table 3).

Effect of TOC and depth on labile carbon fraction and chemical properties

The PCA of the dataset collected for the studied topsoil layers enabled us to identify the parameters which most significantly affected the differentiation of properties in the topsoil of peatlands under the influence of a mursh-forming process. In the PCA analysis, we focused on two principal components, which explained more than half of the variance. However, depending on the TOC content or the layer depth in the topsoil, various parameters were correlated with the principal components (Table 4, Figure 5).

The PCA analysis revealed that the OM, TOC, labile carbon fractions and soil sorption properties like CEC and SBS were strongly correlated (Figure 5). In the layers with the TOC content < 30% (group A), the PC1 and PC2 accounted for 58.45% of variability. The differentiation of peatland topsoil properties in this group was most strongly influenced by the content of organic matter, total organic carbon, HWC, and soil sorption properties (excluding Mg^{2+} and K^{+}) (PC1), as well as Fe, Zn and pH(KCl) (PC2). In the layers with the TOC content > 30% (group B), the PC1 and PC2 accounted for 52.97% of variability, and the properties of peatland topsoil were mainly influenced by the content of organic matter, TOC, HWC, $CaCl_2$-C, soil sorption properties (PC1), and Fe, Mn, Zn, Cu, Mg, K content (PC2) – the correlation coefficients were the highest for these parameters (Table 4, Figure 5).

Different soil parameters dominated the various PCs at different soil depths, and when the depth was taken into consideration, more than 60% of the variability was explained. At 0-10 cm (S1), 63.25% of the variability

Table 4

Correlations between variables and principal components

Parameter	A (< 30% TOC)		B (> 30% TOC)		S1 (0-10 cm)		S2 (10-20 cm)		S3 (20-30 cm)	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
TOC	0.892*	-0.417	0.706*	-0.134	0.833*	-0.467	0.843*	-0.492	0.877*	0.461
OM	0.910*	-0.241	0.715*	-0.199	0.859*	-0.328	0.818*	-0.530	0.882*	0.443
$CaCl_2$-C	0.263	-0.217	0.632*	-0.088	0.548*	-0.469	0.342	0.438	0.845*	-0.161
HWC	0.752*	-0.025	0.793*	0.123	0.902*	0.188	0.642*	-0.082	0.857*	-0.085
CWC	0.593	0.071	-0.532	0.027	0.101	-0.217	0.278	-0.324	0.422	-0.215
Ca^{2+}	0.914*	-0.289	0.948*	-0.222	0.956*	-0.012	0.959*	-0.121	0.962*	0.129
Mg^{2+}	-0.091	-0.348	0.516	0.337	0.408	0.206	0.392	0.605	0.095	-0.439
Na^+	0.896*	-0.380	0.839*	-0.098	0.965*	-0.139	0.973*	-0.147	0.823*	0.383
K^+	0.770*	0.235	-0.369	0.424	0.743*	-0.334	0.883*	-0.295	0.854*	0.295
SBC	0.910*	-0.303	0.952*	-0.177	0.961*	-0.005	0.963*	-0.085	0.960*	0.103
H^+	0.779*	0.468	0.793*	0.294	0.585*	0.591*	0.920*	0.103	0.855*	-0.035
CEC	0.965*	-0.072	0.965*	-0.064	0.954*	0.205	0.969*	-0.041	0.980*	0.075
pH(KCl)	-0.417	-0.638*	0.075	0.027	0.155	-0.430	-0.506	-0.387	0.139	0.001
Ca	0.094	-0.478	-0.006	0.375	0.622*	-0.347	0.134	0.331	-0.446	0.301
Fe	0.572*	0.578*	-0.100	0.805*	0.333	0.736*	0.620	0.335	-0.589	0.672*
Mn	0.559	0.348	-0.120	0.651*	0.405	0.537	0.742*	0.314	-0.207	0.404
Zn	0.149	0.836*	0.377	0.679*	-0.024	0.903*	-0.077	0.899*	-0.011	0.904*
Cu	0.417	0.092	0.247	0.752*	0.606*	0.334	0.444	0.474	-0.398	0.791*
Mg	0.265	0.055	0.047	0.743*	0.467	0.410	0.463	0.063	-0.463	0.575
K	0.603	0.320	0.177	0.606*	0.531	0.593*	0.694*	0.574	-0.807*	0.104

* values correspond to the parameter for which the correlation with the principal component is the largest

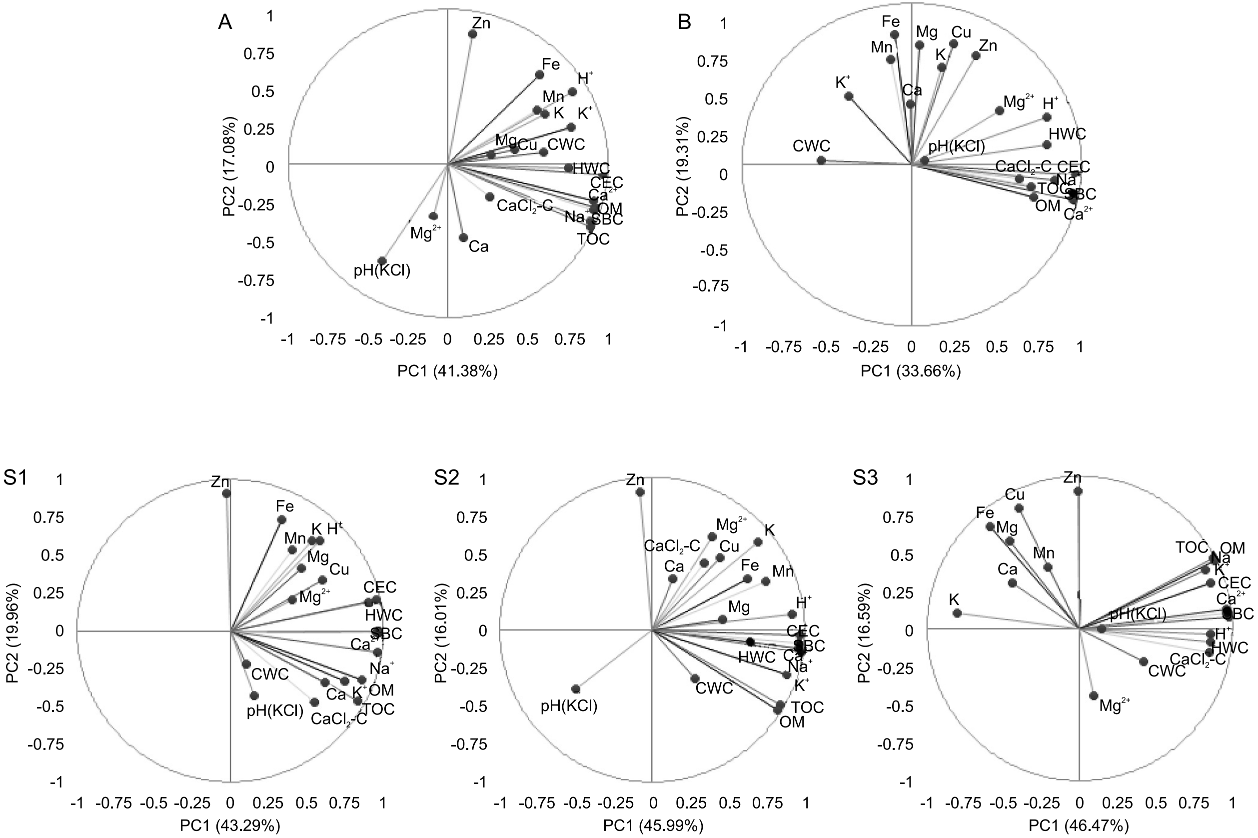

Fig. 5. PCA of dataset studied: A – group of samples with TOC < 30%, B – group of samples with TOC > 30%, S1, S2, S3 – are the sampled depths: 0-10 cm, 10-20 cm and 20-30 cm respectively

was explained by the two PCs, where the PC1 was mostly correlated with OM, TOC, $CaCl_2$-C, HWC, soil sorption properties (excluding Mg^{2+} and H^+), Ca and Cu content, whereas the PC2 was mostly correlated with H^+ and Fe, Zn, K content. At the10-20 cm depth (S2), 62% of the variability was explained by the two PCs, where the PC1 was also correlated with OM, TOC, HWC, sorption properties (excluding Mg^{2+}), but not with $CaCl_2$-C, and PC2 was mostly correlated with the Zn content. At the 20-30 cm depth (S3), 63% of the variability was explained by the two PCs, where the PC1 was correlated with OM, TOC, HWC, $CaCl_2$-C, sorption properties (excluding Mg^{2+}), and PC2 was mostly correlated with the Fe, Mn and Zn content. The differentiation of parameters in the topsoil along with the depth was already noticed for various land uses (Shukla et al. 2023). In the current study, all peatland topsoils were covered by grassland vegetation and were used as meadows. However, the alterations in the mursh-forming process differentiated the three studied depths.

Noteworthy is the fact that none of PCs was correlated with CWC. Similarly to previous studies (Łachacz, Kalisz 2011, Kalisz, Lachacz 2023), CWC, whose concentration cannot be clearly related to alterations in mursh-forming process, proved to be ineffective as an indicator.

The study proved that the soil chemical properties and labile carbon pool vary at studied depths within the mursh horizon. The differentiation of soil parameters in the studied layers of mursh enabled us to characterize how soil chemical properties (soil sorption properties and contents of selected elements) and labile carbon pool respond to the mursh-forming process at three depths in the topsoil: 0-10 cm, 10-20 cm and 20-30 cm as well as at various TOC levels. The soil samples with TOC >30% were more diversified than those with TOC< 30% considering all studied parameters. The differences occurred also along with the depth. The cluster analysis enabled to group the soils and determine which factor, TOC or depth, is more relevant in the context of the properties studied. Three groups of soil samples were identified (C1, C2 and C3, marked in different colours in Figure 6). The first group contained mostly soil samples with < 30% of TOC and those that were in the most superficial 0-10 cm layer (C1; colour blue). The second group of soil samples also comprised soil samples with < 30% of TOC and those that were in deeper layers (10-20 cm and 20-30 cm) – C2; colour red. The third group comprised soil samples with > 30% of TOC and those that were also in deeper layers (10-20 cm and 20-30 cm) – C3; colour green. C2 is similar to C3 group (Figure 6), therefore the soils at 10-20 cm and 20-30 cm, irrespective of the TOC content, are more alike to each other. The uppermost layer with < 30% of TOC in the mursh horizon distinguished itself among all the other layers. Other authors reported similar results, and named the uppermost layer of organic soil a stress-sensitive zone (Hamkalo and Bedernichek 2014).

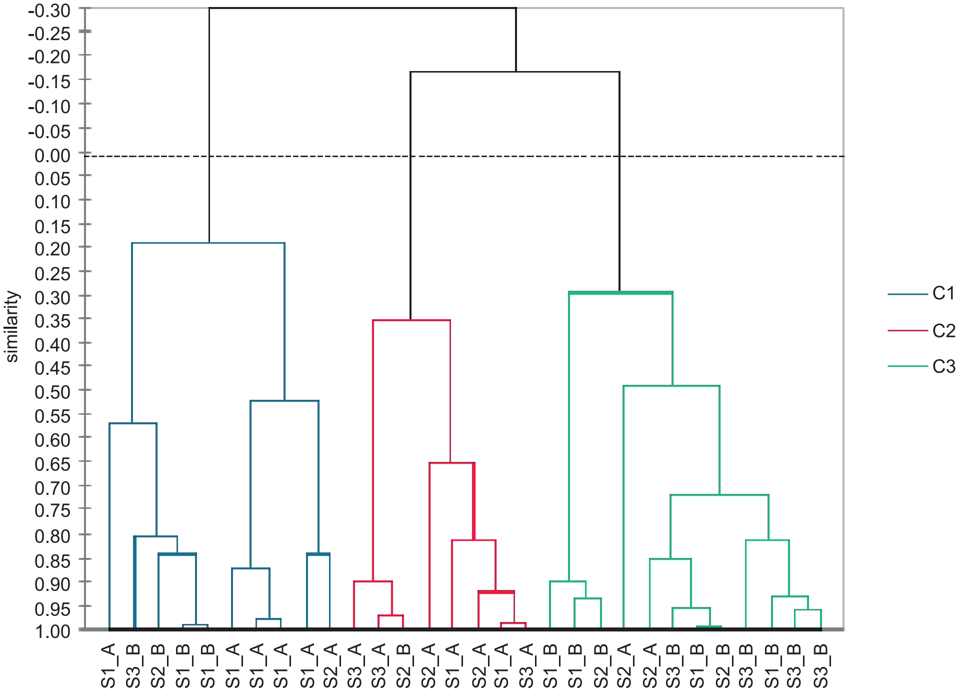

Fig. 6. The similarity of studied soils cluster analysis; the horizontal axis: A – group of samples with TOC < 30%, B – group of samples with TOC > 30%, S1, S2, S3 – are the sampled depths: 0-10 cm, 10-20 cm and 20-30 cm, respectively

CONCLUSIONS

The study proved that the soil chemical properties and labile carbon pool vary at the studied depths of the mursh horizon. The mursh horizon is not homogenous, and the differentiation of soil parameters in the studied layers enabled us to characterize how soil chemical properties (soil sorption properties and contents of selected elements) and labile carbon pool respond to the mursh-forming process at three depths in the topsoil: 0-10 cm, 10-20 cm and 20-30 cm, as well as at various TOC levels. The soil samples with TOC >30% were more diversified than those with TOC< 30% considering all studied parameters. The differences occurred also along with the depth, and the depth turned out to be the best grouping factor. The uppermost layer of mursh horizon (0-10 cm) seemed to differ greatly from the 10-20 cm and 20-30 cm layers.

Additionally, most of decomposable and mineralizable organic matter occurred in the 10-20 cm or 20-30 cm layers, especially when HWC or $CaCl_2$-C were taken into account. The variability of the results among studied depths was explained in PCA analysis by organic matter and carbon contents as well as soil sorption properties, Zn content and labile carbon fractions contents, mainly HWC. The study revealed that HWC is an excellent indicator of changes occurring under the mursh-forming process, whereas CWC proved to be ineffective as an indicator. $CaCl_2$-C proved to be a better indicator in deeper horizons or soils with higher TOC contents (on the basis of the PCA).

Authors contributions

B.K. – conceptualization; B.K., A.Ł. – investigation; B.K. – methodology; B.K., A.Ł., J.D., K.Ż-G. – visualization; B.K., J.D., A.Ł., K.Ż-G. – writing – original draft preparation; B.K., K.Ż-G. – writing – review & editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors have neither professional nor financial connections related to the manuscript sent to the Editorial Board.

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