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Effects of peat drainage on labile organic carbon and water repellency in NE Poland

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Abstract: Hot and cold water-extractable organic carbon (HWC and CWC, respectively) fractions, as good indicators of organic matter quality, as well as water repellency (WDPT test) and state of secondary humification were analyzed in topsoil samples of peatland drained for agricultural purposes 160 years ago. The examined sites (drained and used as grassland) at the peatland had been affected by the moorsh-forming process. During this process, intense mineralization and secondary humification of organic matter took place. The state of transformation of organic soils varied from weak to complete degradation. The HWC contents ranged between 2.623 and 3.572 g kg^{-1} in field-moist samples and 3.999 and 6.074 g kg^{-1} in air-dried soil samples. The CWC contents were generally lower than HWC and ranged between 0.411 and 0.535 g kg^{-1} in field-moist samples and 0.696 and 0.939 g kg^{-1} in air-dried soil samples. The examined soils were extremely water repellent when dried. The measures of transformation of peat after drainage and WDPT were not significantly correlated, but a tendency for higher values of water repellency at the site regarded as degraded was noted. Deep drainage caused an increase of HWC fraction, which in light of the moorsh-forming process should be regarded as negative. The topsoil of the peatland became dry and resistant to rewetting. However, when the ground water level is maintained at not deeper than 0.50 m, the changes in peat matter do not lead to degradation. HWC is a good measure to show differences occurring within the ecosystem. Given its correlation with state of transformation (W1 index) and water repellency (WDPT test), HWC is a good measurement of peat quality. HWC and WDPT measurements may be helpful in determining degradation of peat soil after drainage.

Key words: Dissolved organic carbon, fens, grasslands, moorsh-forming process, hydrophobicity

1. Introduction

A great percentage of the earth's active carbon is located in organic soil matter (Gärdenäs et al., 2011). It is considered as an indicator of soil resistance to negative anthropogenic and natural factors (Šlepetienė et al., 2010) and can be divided into labile and refractory carbon forms (Lützow et al., 2007). Labile fractions of organic carbon (microbial biomass C, fractions of dissolved organic carbon, hot water-extractable carbon [HWC]) can respond rapidly to changes in C supply (Zhang et al., 2006) and therefore are suggested as good indicators of the effects of land use changes on soil organic matter quality (Silveira, 2005). The hot water extractions provide quantitative data on the predictions of the mineralizable C (Körschens et al., 1998; Sparling et al., 1998). Cold water extraction provides data on easily mineralizable carbon (Ghani et al., 2003). HWC is the fraction of organic matter that is naturally labile; its content is correlated with the mass of microorganisms and it is a good indicator of qualitative changes in organic matter (Sparling et al., 1998). This fraction is potentially the most susceptible to oxidation to CO_2 and therefore has the greatest impact on global climate change (Zhang et al., 2007).

Although peatlands cover the area of only 3% of the earth's surface, they are effective accumulators of organic plant material (Berglund and Berglund, 2010) and create one of the largest carbon reserves. Peat consists of plant tissues at various stages of decomposition, humus, and mineral matter (ash). Many peatlands were artificially drained by various drainage systems all over the world to obtain fertile land for agriculture. Under conditions of climatic changes, rising temperatures, and changing water conditions, peatlands are also dewatered naturally (i.e. without direct human activity). Drainage and cultivation of peat soils increase soil aeration, mineralization of organic matter, and release of CO_2 into the ambient air. In such conditions, peat soils undergo serious transformations known as the moorsh-forming process (Ilnicki and Zeitz, 2003; Okruszko and Ilnicki, 2003), leading to changes in peat soil morphology, structure (formation of grains), soil

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physical properties (increasing bulk density, changing relation in water/air properties), and chemical properties. Transformation of peat into moorsh in aerobic conditions after drainage is called the secondary transformation (primary transformation took place during the peat-forming process) of organic matter and causes changes in peat quality (Sokołowska et al., 2005).

Soil organic matter (SOM) quality in peatlands and its stability towards oxidation can be characterized by determination of the different organic carbon fractions of labile and more stable (recalcitrant) compounds. Particularly, the labile or decomposable carbon fraction is of great interest as it is part of the SOM, which can easily be oxidized and released as CO_2 into the atmosphere (Kalisz et al., 2010). In the context of climate change, peatlands can be either a sink or a source of carbon (Delarue et al., 2011).

Another aspect of drainage effects is the decreasing ability of peats to retain water. Water repellency (hydrophobicity), a tendency of a surface not to absorb water, and wettability (hydrophilicity), a tendency to become wetted by surface water, are phenomena applicable to porous solid bodies, including soil. According to research findings, hydrophobic organic substances (mostly present in the surface layer of soil) are among the main causes of water repellency of soil (Wallis and Horne, 1992). Water repellency impairs the soil's capacity to effectively retain water (Lichner et al., 2012). Water repellency is considered to be a negative soil property as it increases the risk of environmental degradation and reduces agricultural production. Despite the fact that water repellency is affected by organic matter content, there are very few published sources investigating this phenomenon in organic soils (Wallis and Horne, 1992; Berglund and Berglund, 2010).

There are numerous findings on the dynamics of SOM in mineral soils (Šlepetienė et al., 2010), but not enough is known about the changes in SOM of peatland soils, especially fen peatland soils. They occur in basins of former lakes (postlake and lakeside fens) and in river valleys (Kalembasa et al., 2009). These peatlands are covered by eutrophic vegetation (grasses, rushes, sedges, trees). In central Europe fens occupy large areas. As was noted by Heller and Zeitz (2012), many publications present data on SOM quality in peatlands, but most of them are related to boreal (northern) peatlands. Not enough is known on fen peatlands that were drained and transformed into meadows or pastures (Gnatowski et al., 2010). Vast areas were later abandoned by their owners. Peatland drainage is considered a degradation in environmental terms because the peatland can no longer fulfil its functions as a carbon sink and a water retainer.

The aim of the present study was to assess how drainage affects the content of labile carbon, water repellency, and water-holding capacity in fen peatland in the context of peatland degradation.

2. Materials and methods

2.1. Study area

The study area is located in northeastern Poland (Figure 1), in a region called the Great Mazurian Lakeland, near Szymonskie Lake, with the following coordinates: 53°54′29″N, 21°38′41″E. The highest temperature in this area is in July (17.5 °C) and the lowest is in February (–4.7

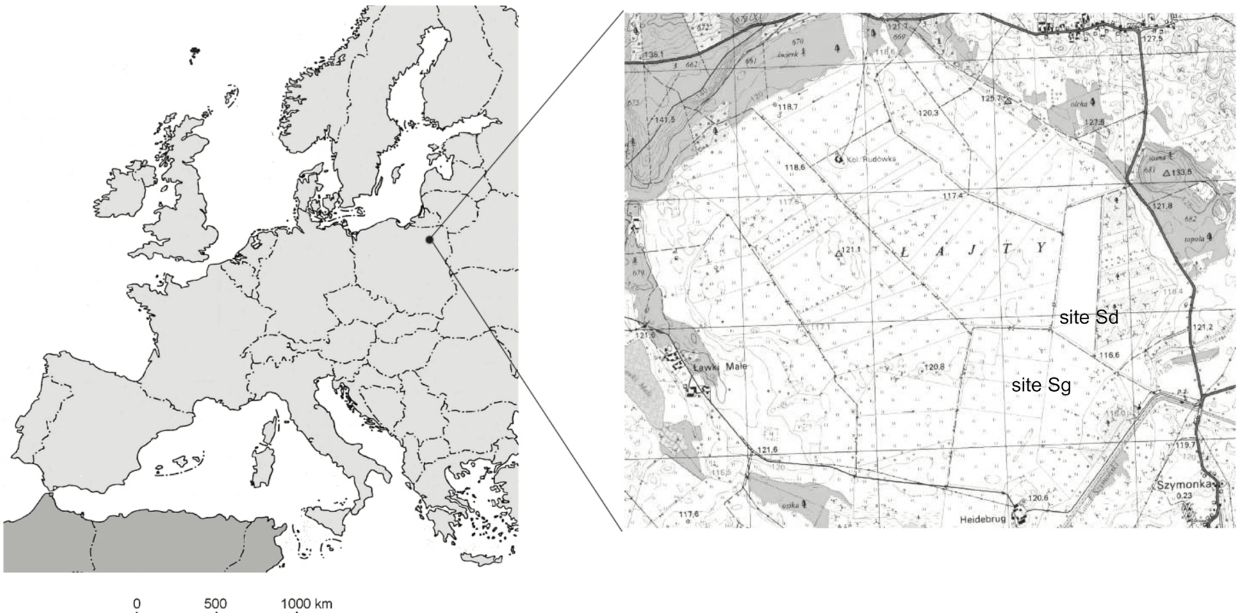

Figure 1. Location of the studied area.

°C). The frosts last from October until early May and the growing seasons last 194 days. Mean average precipitation is 529 mm. The relief of the Great Mazurian Lakeland was shaped during the Vistulian Glaciation (the last glacial period). Specific features of the region are latitudinal moraines, numerous lakes, and wetlands. The investigated site is a large fen peatland (1500 ha) of lacustrine origin that was formed from highly decomposed alder, rush, and sedge peats. It was drained 160 years ago with open ditches and a moorsh-forming process was initiated. Since then, the peatland has been used in agriculture as arable fields (mainly the edges), pastures, and meadows. Nowadays the water level in the main ditches is deep (1–1.5 m below the surface) and large areas are used as arable fields. Parts of the peatland are used as grassland and some areas are not used at all. We chose a part of the peatland that has not been mowed for several years (site Sd – deeply drained soil) and an extensive grassland area (site Sg – grassland soil) for our study. Figure 1 shows the location of the studied areas.

The topsoil of site Sd was pulverized and the moorsh was loose and fine-grained, covered with the herbaceous grass vegetation typical for dried sites. The most common among the plant species were *Holcus lanatus*, *Festuca rubra*, *Achillea ptarmica*, *Cardaminopsis arenosa*, *Rumex acetosa*, *Linaria vulgaris*, and *Ranunculus auricomus*. Pulverized and fine-grained moorsh indicates advanced moorsh-forming processes (soil aggregates formed after drainage become smaller, powdery) and that this part of peatland may be regarded as degraded, i.e. it has lost the ability to fulfill its functions. At the other studied site of the peatland (Sg), the moorsh was humus-peaty and the site was used as an extensive grassland with vegetation typical for moist meadows: *Phragmites australis*, *Phalaris arundinacea*, *Cirsium oleraceum*, *Mentha arvensis*, *Anthriscus sylvestris*, and *Urtica dioica*.

2.2. Soil sampling and methods

At each site, soil samples were collected from 4 points from depths of 0–10 cm, 10–20 cm, and 20–30 cm. Loss on ignition (LOI) was determined after dry ashing of soil samples for 6 h at a temperature of 550 °C. Total organic carbon (TOC) content was measured with a spectrophotometer after oxidation with potassium dichromate according to ISO Standard 14235 (International Organization for Standardization, 1998). Total nitrogen (TN) was measured by the Kjeldahl method. Soil reaction was determined potentiometrically in potassium chloride solution (1 M KCl dm^{-3}) and soil bulk density was measured in undisturbed soil cores of 100 cm^3 (van Reeuwijk, 2002). The analyses of LOI, TOC, TN, and soil bulk density were performed in duplicate and the results were expressed on an oven-dried soil weight basis (dried at 105 °C).

State of secondary transformation of the studied soil samples was estimated with the water-holding capacity method (Gawlik, 1992). This index was determined by dividing the water capacity of a soil sample that was absolutely dry (dried at 105 °C) by its water capacity in a natural (field-moisture) state. Briefly, the fresh soil material was divided into 2 parts. The first was soaked in distilled water for 7 days, put onto a sieve of 1.0 mm in diameter, and centrifuged at 1000 × *g* for 1 h. Following this, the amount of water in the soil sample was determined gravimetrically (a). The second part was oven-dried at 105 °C, soaked in distilled water for 7 days, put onto a sieve, and centrifuged at 1000 × *g* for 1 h. The amount of water in the soil sample was then determined (b). The state of transformation of the studied soil samples was determined on the basis of the water-holding capacity index W1, calculated from the following formula: W1 = b / a. The analysis was performed in duplicate

The results were later compared to the transformation classes (Table 1) proposed by Gawlik (2000).

The hot water-extractable C (HWC) was determined in field-moist and air-dried soil samples according to the method described by Sparling et al. (1998). Briefly, 4 g of air-dried soil was incubated with 20 mL of demineralized water in a capped test tube at 70 °C for 18 h. The tubes were shaken by hand at the end of the incubation and then filtered through Whatman ME 25/21 ST 0.45-µm membrane filters (mixed cellulose ester). Cold water-extractable carbon (CWC) was determined in field-moist and air-dried soil samples according to Landgraf et al. (2006). CWC extracts were obtained by shaking 10-g aliquots of soil samples with 10 mL of deionized water horizontally at 180 rev min^{-1} for 24 h. The suspension was then centrifuged at 4000 rev min^{-1} for 10 min and decanted. The HWC and CWC quantities were measured on a TOC analyzer (TOC 550 Hach Lange) in triplicate.

Water repellency was determined on the basis of the water drop penetration time (WDPT) test (Doerr, 1998). The investigated samples were air-dried and the test was performed at a temperature of 20 °C. A standard medical syringe was used to place 5 drops of distilled

Table 1. State of transformation according to W1 index.

W1	Class	State of transformation
0.36–0.45	I	Initially secondarily transformed
0.46–0.60	II	Weakly secondarily transformed
0.61–0.75	III	Moderately secondarily transformed
0.76–0.90	IV	Strongly secondarily transformed
>0.90	V	Completely degraded

water on a homogenized and smoothed soil surface, and the arithmetic mean of time was calculated. The results indicate potential water repellency (Dekker and Ritsema, 1994). The analyses were performed in quadruplicate. The soils for which water drop penetration time was less than 60 s were regarded as hydrophilic; when the WDPT exceeded 3600 s they were regarded as extremely hydrophobic (or water-repellent) (after Doerr, 1998).

Statistical analyses were conducted with Statistica 9.0.

3. Results

In the investigated peatland, bulk density values were the highest in the layer of 0–10 cm at site Sd and decreased with depth. At the site of the peatland that was used as grassland (Sg), bulk density was lower and also decreased with depth (Table 2). Sampling-time moisture and pH values were lower at site Sd and increased with depth. The amounts of TN ranged between 23 and 29 g kg^{-1} and were higher at site Sd (Table 2).

The amounts of TOC at both investigated parts of the peatland ranged between 308 g kg^{-1} and 517 g kg^{-1}. The lowest TOC concentrations were found in the top layers at site Sd. The TOC/TN ratio was between 10 and 17, reaching higher values in deeper layers (Table 2).

The values of the W1 index were lowest at site Sg. This part of peatland was classified as medium and weakly secondary transformed (Tables 1 and 2). Site Sd had higher values of the W1 index, up to above 0.90 (the highest class of transformation according to Tables 1 and 2) in the top layer.

Water repellency of the studied soil samples, expressed as water drop penetration time, is shown in Figure 2 (in quadruplicates). All examined samples were extremely water-repellent (Doerr, 1998). The longest time of water drop penetration was noted at site Sd. The part of the peatland that is used as grassland (Sg) showed lower times of water absorption that increased with depth but were still lower than at site Sd.

The state of transformation of peat after drainage (expressed as W1) and WDPT values were not significantly correlated (Figure 3), but a tendency for higher values of water repellency at the site assumed to be degraded (Sd) was noted.

The results of soil labile carbon measurements are shown in Figure 4. The HWC and CWC in air-dried and field-moist soil samples showed similar tendencies. Generally, HWC concentrations were higher in air-dried soil samples than in field-moist samples. The HWC contents ranged between 2.623 g kg^{-1} and 3.572 g kg^{-1} in field-moist samples and 3.999 g kg^{-1} and 6.074 g kg^{-1} in air-dried soil samples. Air-dried and field-moist extracts of HWC were correlated (Figure 5; the critical value of the correlation coefficient is 0.472 at $P \leq 0.01$ and 0.344 at $P \leq 0.05$). The highest HWC content was found at site Sd and the lowest at site Sg. It was also noted that the concentrations of HWC were the highest at depths of 10–20 cm and the lowest at 20–30 cm.

The CWC contents were generally lower than HWC and ranged between 0.411 g kg^{-1} and 0.535 g kg^{-1} in field-moist samples and 0.696 g kg^{-1} and 0.939 g kg^{-1} in air-dried soil samples. Contents of CWC in air-dried and field-moist samples were not correlated (Figure 5).

4. Discussion

The investigated sites of the peatland were both influenced by human activity (drainage and agricultural use). In the 1940s, the peatland was rewetted (the drainage network was not maintained as a result of the Second World War), and 20 years later it was drained once again. Consequently, decomposition of soil organic compounds, soil

Table 2. Main characteristics of the studied soil samples (mean from each site).

Site	Mean groundwater level	Depth	BD	Moisture at sampling time	LOI	TOC	TN	TOC/TN	pH (KCl)	W1	Class of transformation according to W1
	cm		g cm^{-3}	% vol.	g kg^{-1}						
Sd	95	0–10	0.401 (0.018)	49.84 (13.03)	787 (10.2)	308 (6.13)	29.32 (1.67)	10.51	4.45	0.91	V
		10–20	0.376 (0.028)	60.44 (3.36)	810 (8.4)	386 (2.21)	28.11 (0.64)	13.74	4.81	0.83	IV
		20–30	0.296 (0.026)	68.71 (4.32)	846 (12.1)	448 (10.83)	25.62 (1.03)	17.49	5.74	0.74	III
Sg	45	0–10	0.373 (0.075)	68.52 (3.14)	833 (6.1)	483 (0.74)	25.90 (3.05)	12.00	6.18	0.73	III
		10–20	0.332 (0.076)	68.93 (3.79)	752 (5.3)	435 (2.31)	25.35 (1.05)	16.72	6.08	0.65	III
		20–30	0.270 (0.058)	73.30 (4.60)	892 (2.3)	517 (1.51)	23.60 (3.92)	17.48	6.11	0.48	II

BD – Dry bulk density, LOI – loss on ignition, TOC – total organic carbon, TN – total nitrogen; values in parentheses are standard deviations.

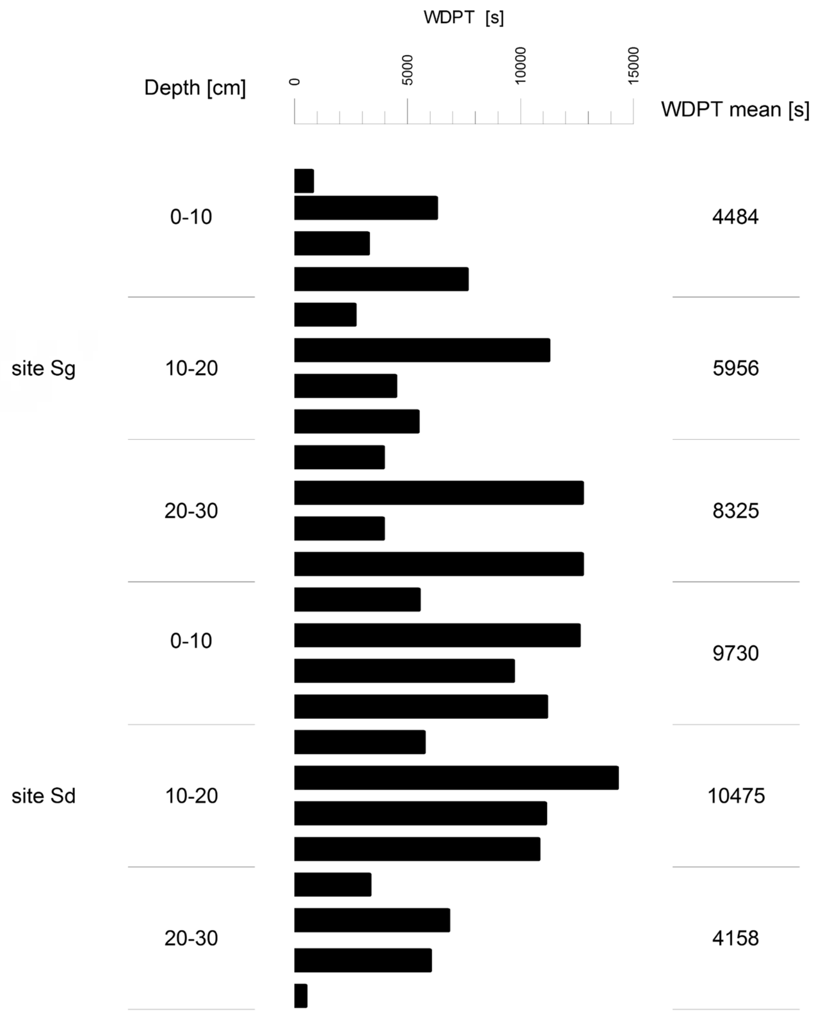

Figure 2. Water drop penetration time measured in studied soil samples.

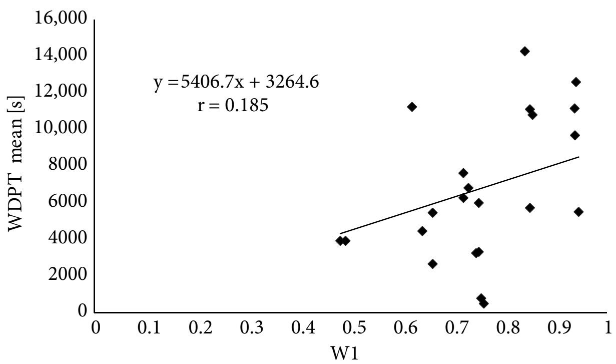

Figure 3. Dependence of WDPT on the state of peat transformation (n = 24; P < 0.05).

compaction, and subsidence of the peatland took place. In the meantime, the drainage ditches were deepened several times to lower the groundwater level. The organic matter at the edges of the peatland was highly oxidized and these parts of the peatland are nowadays used as plow land (mineral or mineral-organic soils), but some plots are not agriculturally used for plant production (fallow, with groundwater level below 0.95 m during the growing season). Other parts, where the groundwater level is higher (ca. 0.50 m below the surface during growing season), are used as grasslands.

In reclaimed peatlands the groundwater level depends on the distance from the ditches that drain the soil. In plots located close to the ditches, the groundwater level is deep. Further from the ditches the groundwater level tends to be closer to the surface. The investigated peatland underwent moorsh-forming processes and secondary humification of organic matter. That resulted in aeration of topsoil, decomposition of organic matter, leaching of biogenic compounds, and consequently changes in the

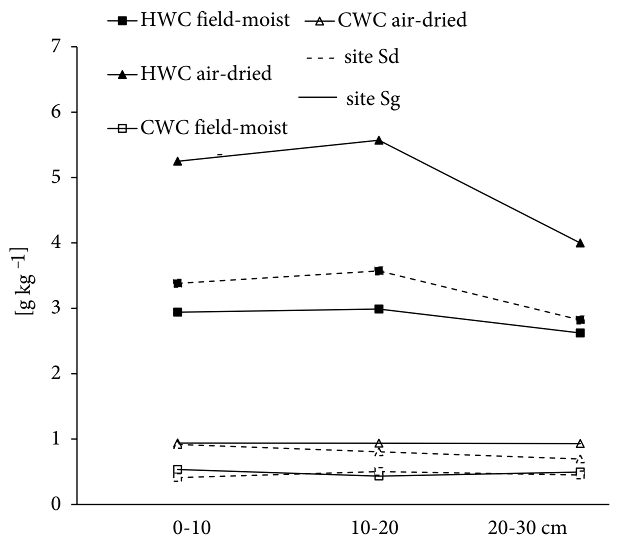

Figure 4. Amounts of extracted hot water carbon (HWC) and cold water carbon (CWC) in studied top soils of peatland.

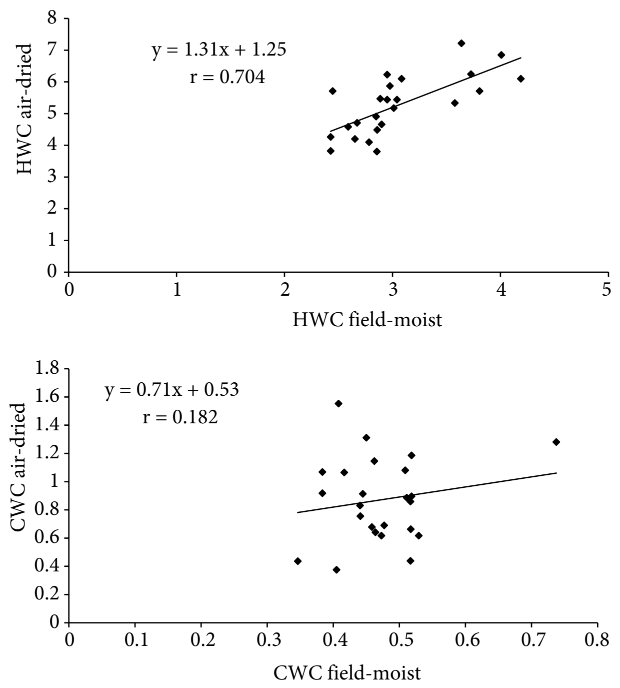

Figure 5. Relation between field-moist and air-dried soil samples of CWC and HWC, g kg^{-1} (n = 24; P < 0.05).

physical and chemical properties of the soil. Considering the above processes, it is not surprising that some sites of the peatland areas that we studied were too dry while others tended to reswamp.

Following drainage, the bulk density in the studied peatland layers decreased with depth, which is typical for drained fen soils (Mueller et al., 2007; Heller and Zeitz, 2012). Moorsh-forming processes occurring in the drained peat soils initiated the process of decalcification, which involves the leaching of base cations (mainly calcium and magnesium), manifested by acidification and lowering of pH values. The amounts of organic carbon were also lower in surface layers, consistent with the results of other researchers (Okruszko and Ilnicki, 2003). The part of the peatland that was deeply drained (Sd) was well aerated, which favored mineralization of organic matter and probably release of CO_2 into the air (Zhang et al., 2007). Heller and Zeitz (2012) stated that originally accumulated SOM disappears during moorsh-forming processes.

It should be noted that the layers of 20–30 cm at both investigated sites have similar properties, suggesting similar origin: both sites were formed from the same genetic type of peat, but after drainage the uppermost layer gained different properties as a result of different site conditions (depth of drainage, groundwater level, water availability).

According to the W1 index, the Sd surface layer is completely degraded. Dense grains of moorsh act as gravel and do not absorb water. Although the W1 index decreased with depth, it was still higher at site Sd than at site Sg. The unused part of the peatland (Sd) should be regarded as degraded because of its decreased ability to hold water after drying, which was also confirmed by the WDPT test. Consequently, during summer time the top layer is frequently dry and does not absorb water after rain.

Water repellency in soils rich in organic matter, i.e. peat soils and peaty (mineral-organic) soils, is dependent on organic matter content and is clearly manifested only when organic matter content exceeds 20% (Lachacz et al., 2009). It is known that water repellency of mineral soils contributes to water erosion and preferential water flow. In organic soils it causes the disturbance of key soil functions related to water flow and water storage. It is thought that irreversible drying of organic matter is one of the main causes of water repellency of soil (Lachacz et al., 2009), which is particularly important in drained peatlands as they can no longer fulfill the role of a "sponge" for water. However, the time the soil needs to absorb water varies greatly, which has been noted in previous studies (Lachacz et al., 2009; Orzechowski et al., 2013). It should also be noted that we investigated the potential water repellency in air-dried soil samples at the sites that were differently influenced by the moorsh-forming processes. This state of water repellency is reached by the soil surface during summer months without precipitation.

It was noted that the concentrations of HWC were highest at 10–20 cm of depth and lowest at 20–30 cm. The obtained results of HWC suggest that the highest amounts of mineralizable C occur immediately below the surface root layer (0–10 cm) but do not increase with depth in the soil profile. This indicates that in field conditions water-soluble carbon compounds are not washed into deeper layers as noted by some other authors (Gonet et al., 2009).

The CWC contents were generally lower than HWC, which was also noted by Landgraf et al. (2006). It should also be stated that, similarly to HWC contents, CWC amounts in organic soil samples were higher than those in mineral soil samples examined by Jandl and Sollins (1997) and Gregorich et al. (1996), which should be regarded as typical and connected to the higher amounts of carbon in organic soils.

Our study indicated that drainage contributed to the increase of HWC in surface layers of peatland and also to the increase of water repellency, expressed as WDPT. We noted that these 2 parameters were correlated at the site that we assumed to be a degraded part of the peatland (Sd) (Figure 6). Compact, dense vegetation at the site used as grassland (Sg) protects the soil surface against overheating during summer drought, and there is a lasting input of fresh, easily decomposable plant debris, mainly roots of grasses (Okruszko and Ilnicki, 2003). Another important factor is peatland use: proper use as an extensive grassland seemed to diminish water repellency as compared with the unused parts of the peatland.

The state of secondary transformation expressed with the W1 index corresponds to HWC (Figure 7). The changes occurring in peat organic matter (induced by drainage) are related to microbial activity expressed as HWC. This proves that HWC is a good indicator of qualitative changes in the soil. Generally, high amounts of HWC are regarded as favorable, but in the context of moorsh-forming processes

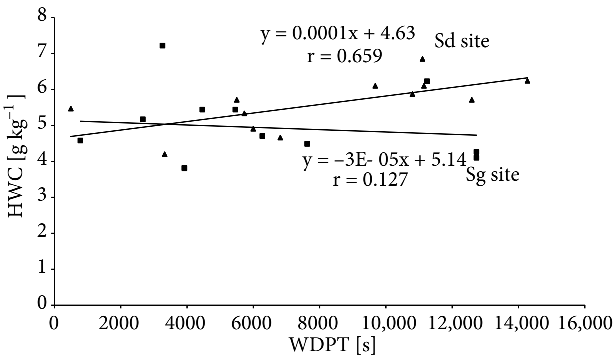

Figure 6. Relation between HWC (air-dried samples) and WDPT (n = 24; P < 0.05).

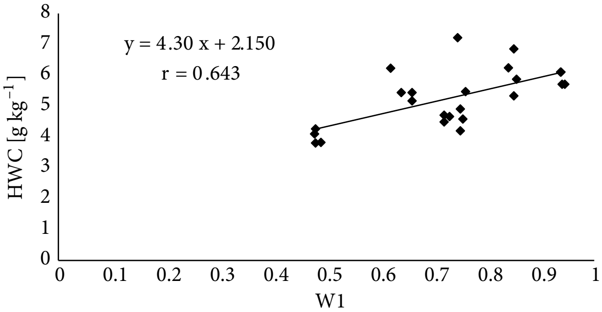

Figure 7. Relation between HWC (air-dried samples) and W1 (n = 24; P < 0.05).

and changes in peatlands, it is negative (higher microbial activity suggests ongoing moorsh-forming processes and lower OC amounts and lower pH values).

Long-lasting lowering of groundwater levels contributed to the differentiation of peatland soil properties, called moorsh-forming processes. Drainage of the peatland commenced moorsh-forming processes and the loss of organic carbon. Deep drainage at site Sd caused an increase of HWC, an indicator of microbial activity. Generally, in the context of agricultural use, higher amounts of HWC indicate good soil quality. However, in peat soils, in the light of moorsh-forming processes, it should be regarded as negative because of the enhanced microbial decomposition of organic compounds, the decrease of carbon sequestration, and probably the release of CO_2 into the air. The topsoil of peatland became dry and resistant to rewetting; it became extremely water-repellent due to changes induced by the moorsh-forming processes. These soils no longer play the role of peat soils (i.e. a sink for carbon and a sponge for water) and should be regarded as degraded. However, when the ground water level is maintained at not deeper than 0.50 m, the negative changes in soil are minimal.

In conclusion, it should be noted that HWC is a better soil quality indicator than CWC. HWC is a good measure to display differences occurring within the peatland ecosystem. Sample moisture influences the amounts of HWC, with a tendency for higher values in air-dried samples. Given its correlation with the state of secondary transformation (W1 index) and water repellency (WDPT test), HWC is a good measurement of peat quality. Both HWC and WDPT measurements may be helpful in determining degradation of peat soil following drainage.

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