The effect of long-term forestry drainage on the current state of peatland soils: A case study from the Central Sudetes, SW Poland

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SUMMARY

One important need in the context of peatland restoration is to gain knowledge of soil organic matter quality and current soil-forming process in degraded peatlands. The aim of this study was to evaluate the impact of long-term drainage on soil transformation processes. In autumn 2012, soil survey and sampling was carried out on five shallow peatlands in the Central Sudeten Mountains (Poland) which had been drained for forestry use in the late 1800s or early 1900s. Four organic soils (Histosols) and one organo-mineral soil (Histic Gleysol) were studied. The surface soil horizons were mainly transformed due to long-term forestry drainage. Increased aeration of these layers had enhanced their content of labile forms of carbon and they were undergoing secondary transformation. Soil transformation was more advanced in fen peatlands than in transitional mire or raised bogs. Only the fens exhibited characteristic evidence of the moorsh-forming process. Further drying of these soils will negatively affect their rewetting potential and significantly reduce the effective application of restoration treatments. In order to reduce organic matter transformation and loss from the investigated peatland areas, their drainage ditches should be blocked. Additionally, some trees should be removed from their central areas to reduce evapotranspiration.

KEY WORDS: organic matter, peatland forestry, soil transformation, Sudeten Mountains

INTRODUCTION

During the last century, natural peatlands in central and western Europe were strongly influenced by a range of human activities (Heller & Zeitz 2012, Łabaz & Kabała 2016). Mountain peatlands were particularly affected by forestry (Yallop & Clutterbuck 2009, Łajczak 2013, Benavides 2014). Around the beginning of the 20th century, large mire areas in the Central Sudetes (Poland) were intensively drained for forestry management (Stark 1936) of Norway spruce *Picea abies* (Gałka *et al.* 2014). The effectiveness of drainage depends on rainfall, evapotranspiration, topography, soil properties, vegetation cover and drainage techniques (Paavilainen & Päivänen 1995); and these factors are particularly relevant for peatlands in mountain areas with varied topography (Łajczak 2013, Glina 2014).

Management involving drainage causes multidirectional changes in peatland hydrology, as well as in the physical and chemical properties of the peat (organic soil) (Prévost *et al.* 1999, Wüst-Galley *et al.* 2016), the changes being faster in minerotrophic fens than in oligotrophic bogs (Ilnicki & Zeitz 2003). Changes are observed in peat structure (Minkkinen & Laine 1998) and susceptibility to runoff erosion (Holden *et al.* 2007), as well as in leaching of nutrients (Sallantaus 1995) and dissolved organic carbon (DOC) (Kalisz *et al.* 2015). The labile DOC fraction of soil organic carbon is regarded as the earliest noticeable indicator of transformations in soil organic matter (Chen *et al.* 2009) and plays an important role in soil chemical and biological processes including the transport of nutrients, metals and pollutants (Zhang *et al.* 2007, Laik *et al.* 2009).

Although interest in the influence of human activities on the current state of European peatlands has previously focused most strongly on lowland sites (e.g. Heller & Zeitz 2012, Kalisz *et al.* 2010, Kalisz *et al.* 2015, Glina *et al*. 2016b), the issue is also worthy of discussion in the context of degraded mountain mires (Yallop & Clutterbuck 2009, Łajczak 2013, Benavides 2014). The main objective of the research described here was to assess the current stage of soil degradation that has resulted from long-term forestry drainage of peatlands in the Central Sudetes. This is used to address the question of whether old drainage networks still significantly affect shallow peatland soils in Stołowe Mountains. The information we have obtained about soil organic matter quality and current soil-forming processes in degraded peatlands will be used during planning and execution of imminent restoration programmes for the study sites.

METHODS

Study sites

The study sites are located in the Stołowe Mountains, which rise to a maximum altitude of 919 m a.s.l. (Szczeliniec Wielki) in the central part of the Sudetes range in south-west Poland (Figure 1). The area of peatland in the Stołowe Mountains is currently 132 ha, although this total represents only the residual portions of mire complexes that were once much larger and have undergone degradation processes (Bogacz & Glina 2015). This part of the Sudetes is formed by upper Cretaceous sandstones with concomitant fine-grained sandstones, siltstones (mudstones) and claystones (Wojewoda *et al.* 2011). The climate is temperate (Łabaz *et al.* 2014). Mean annual air temperature is 4.8 °C, with the highest monthly mean temperature (16.9 °C) occurring in July and the lowest (-7.3 °C) in January. Mean annual precipitation increases with altitude from 750 to 920 mm and the wettest month is July (mean rainfall >1150 mm). Snow cover persists for 70–95 days, depending on altitude, between the end of November and the end of April (Gałka *et al*. 2014).

Five peatland sites (A, B, C, D and E) were selected for this study, and a sampling plot (square, 5 m × 5 m) was established in the central part of each site (Table 1). Plots A and B were located on the raised bogs Niknąca Łąka (A) and Długie Mokradło (B). These peatlands developed on sandstone bedrock and are supplied with water primarily by atmospheric deposition (ombrogenous type) (Glina *et al.* 2016a). Sampling Plot C was sited on very shallow transitional bog at Rogowa Kopa. The sites for Plots D and E were spring fen peatlands located on the steep slopes of the Skalniak ridge. These mires developed on sparingly permeable loamy or silty bedrock and the dominant component of their water supply is soligenous

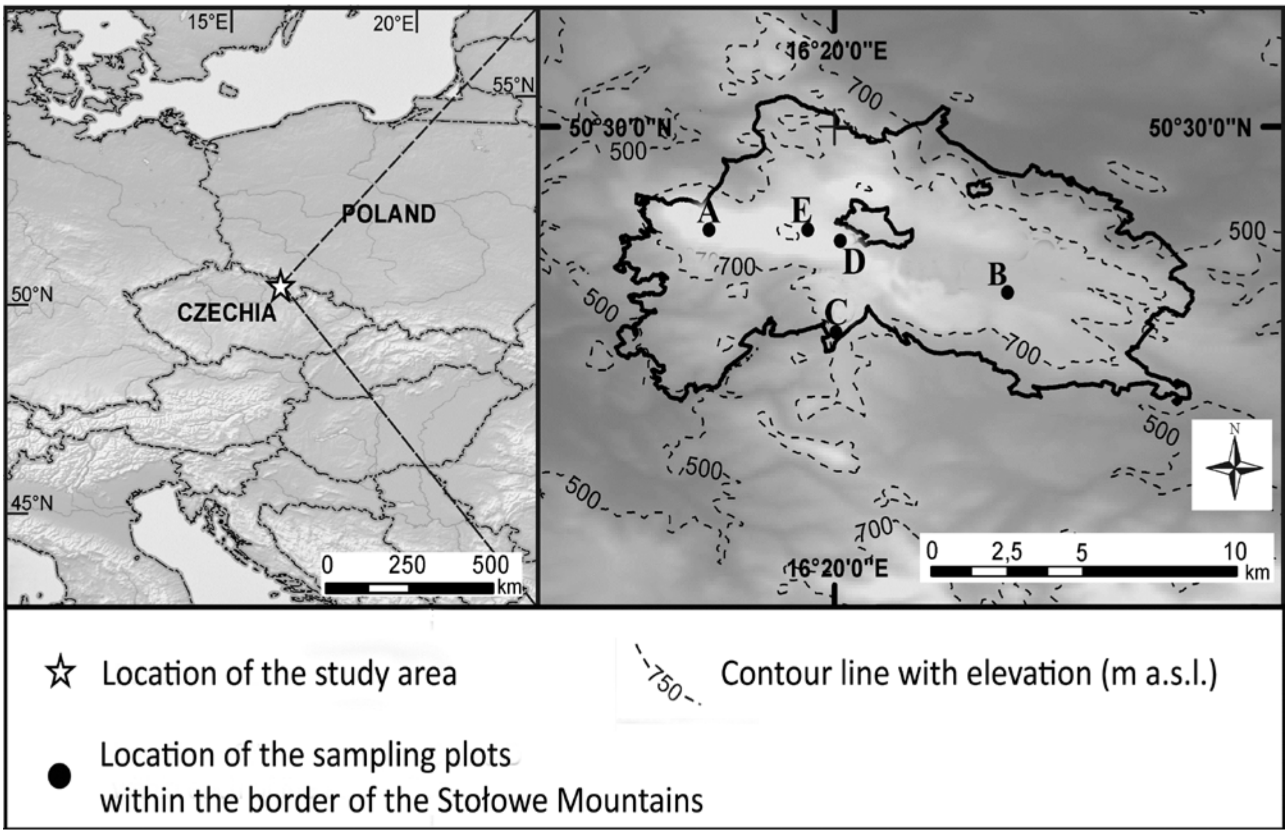

Figure 1. Location map of the study sites.

Table 1. Characteristics of the sampling sites.

Study site	Coordinates WGS 84 (N/E)	Altitude (m a.s.l.)	Site	Total area (ha)	Ground water level (m b.g.l.)	Vegetation	Sampling depth (cm)	Soil order (WRB 2015)
A	50° 27′ 57.8″ N 16° 23′ 37.7″ E	717	Niknąca Łąka	4.05	0.15	Coniferous forest	0–54	Dystric Ombric Drainic Fibric Histosol
B	50° 28′ 22.8″ N 16° 17′ 48.8″ E	847	Długie Mokradło	4.50	0.40	Coniferous forest	0–50	Dystric Ombric Drainic Fibric Histosol
C	50° 26′ 55.2″ N 16° 20′ 11.8″ E	753	Rogowa Kopa	2.05	0.20	Mixed forest	0–32	Dystric Drainic Histic Gleysol
D	50° 28′ 05.6″ N 16° 20′ 21.8″ E	767	Skalniak ridge	0.75	0.15	Coniferous forest	0–80	Eutric Rheic Murshic Sapric Histosol (Lignic)
E	50° 28′ 20.9″ N 16° 19′ 40.7″ E	792	Skalniak ridge	0.95	0.35	Coniferous forest	0–49	Eutric Drainic Sapric Histosol

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(groundwater interflow) (Glina *et al.* 2016a). The Rogowa Kopa plateau (Plot C) is covered by more or less dense mixed spruce-birch forest (Glina 2014), and the other four study sites are covered by dense stands of coniferous forest dominated by Norway spruce. All five sites are dissected by more or less dense networks of open drainage ditches (Bogacz & Glina 2015) which have not been cleared for many years (Kabała *et al.* 2011), although it is impossible to determine precisely when ditch maintenance was abandoned. In some places, particularly on the raised bogs, the ditches have become overgrown by natural vegetation or partially infilled with sand (Bogacz *et al.* 2012, Sienkiewicz & Wójcik 2012).

Sampling and analysis

Soil survey and sampling was carried out during the autumn of 2012. At each sampling plot, soil morphology was first described according to the *Guidelines for Soil Description* (Jahn *et al.* 2006). Soils were classified on the basis of morphological features and physico-chemical properties, following the FAO-WRB soil classification (WRB 2015). Representative soil samples for laboratory analysis (three replicates) were collected according to genetic soil horizons (69 samples in total), from the centres of the sampling plots. Separate undisturbed soil samples (100 cm^3) for bulk density determinations were collected using stainless steel rings. Peat cores, 50 cm long, were extracted using an "Instorf" peat corer (diameter 5.2 cm, Ejkelkampf GmbH).

In the laboratory, each soil sample was divided into two parts. The "fresh" part was used to determine degree of decomposition and water holding capacity index (W_1). Degree of decomposition was determined using the fibre volume method. Fibres were separated from the peat samples by sieving (0.15 mm mesh) under running tap water (Lynn *et al.* 1974) and the peat was classified, according to the percentage content of fibre, as fibric (slightly decomposed), hemic (moderately decomposed) or sapric (strongly decomposed) (WRB 2015). State of secondary transformation was estimated using the water-holding capacity index W_1 (Gawlik 2000, Kalisz *et al.* 2015) and the results were later compared to the transformation classes proposed by Gawlik (2000). The other part of each soil sample was dried at 105 °C and, after removal of the plant remains, crushed in a clean agate mortar to yield homogenous powder. In air-dry soil samples the following properties were determined: humification index of organic matter Q_4/Q_6 in 0.5 M NaOH extracts using the spectroscopy method (Sapek & Sapek 1997); ash content by placing dried samples in a muffle furnace at 550 °C for five hours (Bojko & Kabala 2015) with selected samples being tested at 900 °C to check the completeness of the ignition; and potential strength of soil water repellency using the Molarity of an Ethanol Droplet (MED) test (Doerr 1998), which is quicker and more easily performed in the laboratory (Moody & Schlossberg 2010) than the WDPT (Water Drop Penetration Time) test and gives more consistent results (Huffman *et al.* 2001). The MED results, which indicate potential (not actual) water repellency, were compared with the soil water repellency categories (Table 2). Total organic carbon (TOC) and total nitrogen (TN) were measured, respectively, by catalytic dry combustion at 600 °C (Ströhlein CS-mat 5500) and the Kjeldahl method using a Büchii analyser. Content of hot water extractable carbon (HWC) was measured in soil extracts obtained by incubation of soil samples at 70 °C for 18 h (Sparling *et al.* 1998). Cold water carbon (CWC) was determined in soil extracts obtained by shaking 10 g of soil with 10 ml of deionised water at 180 rev min^{-1} for 24 h followed by centrifugation at 4,000 rev min^{-1} for 10 min (Landgraf *et al.* 2006). HWC and CWC were measured using a VarioMax analyser, after filtration of the soil extracts using Whatman 0.45 µm membrane filters. Statistical analyses (Pearson correlation coefficient, cluster analysis and Principal Component Analysis - PCA) were carried out using the Statistica 12 software system (StatSoft Inc., Tulsa, OK).

Table 2. Soil water repellency (Doerr 1998).

Concentration of ethanol solution infiltrate within 3 s (%)	Categories of soil water repellency
0	Very hydrophilic
3	Hydrophilic
5	Slightly hydrophobic
8.5	Moderately hydrophobic
13	Strongly hydrophobic
24	Very strongly hydrophobic
36	Extremely hydrophobic

RESULTS

Soil description and physical properties

According to the FAO-WRB classification (WRB 2015), the soil profiles belonged to the reference groups of Histosols (Plots A, B, D and E) and Gleysols (Plot C) (Table 1). In the uppermost 20 cm of the soil profile at Plot D (fen peatland), weak aggregate structure (peaty moorsh) was observed. This fulfilled the criteria for the "murshic" principal qualifier (drained surface organic horizon, minimum 20 cm thick, with a bulk density of 0.2 kg dm^{-3} and granular or blocky structure) that was recently introduced to the FAO-WRB terminology (WRB 2015). The thickness of the organic layer did not exceed one metre at any of the plots, and this can be linked to intensive subsidence of peat caused by long-term forestry drainage. Macroscopic charcoals were found in the basal peat layer at Plot B.

The soil profiles at Plots C, D and E consisted of strongly decomposed (sapric) peat (fibre content < 10 %), whereas the profiles at Plots A and B were made up of alternating layers of moderately decomposed (hemic, fibre content 16.6–40 %) and slightly decomposed (fibric, fibre content > 40 %) peat (Table 3). The peat from Plot A had the lowest ash (i.e. mineral) content (not exceeding 14.0 %). Ash contents determined for the other sites were mostly in the range 17.0–46.5 %. The highest values of both ash content and bulk density were recorded for organic soil horizons at the transition to mineral bedrock, as well as in topsoil horizons with high admixture of mineral material (e.g. Profile B - Ha1).

Table 3. Physical properties of the soil horizons in Profiles A–E (mean values from three replicates, n = 69).

Profile	Soil horizon	Depth (cm)	RF (%)	BD (g cm^{-3})	Ash content (%)	W_1	State of Secondary Transformation	MED %
A	Hi1	0–10	48	0.109	4.31	0.39	Initial	24
	He	10–19	37	0.151	8.62	0.33	-	24
	Hi2	19–34	50	0.112	5.70	0.27	-	36
	Ha	34–37	14	0.114	11.7	0.35	Initial	36
	He2	37–54	34	0.146	13.7	0.30	-	36
B	Hi1	0–9	41	0.165	18.3	0.52	Weak	13
	Ha1	9–23	10	0.345	63.5	0.55	Weak	36
	Hi2	23–38	45	0.141	12.4	0.30	-	36
	Hi3	38–43	42	0.156	16.2	0.35	-	36
	Ha2	43–50	6	0.311	55.0	0.72	Moderate	36
C	Ha1	0–8	9	0.139	11.9	0.59	Weak	24
	Ha2	8–14	6	0.175	20.9	0.35	Initial	24
	Ha3	14–23	6	0.208	29.1	0.29	-	24
	Ha4	23–32	5	0.331	59.6	0.35	Initial	24
D	M1	0–12	10	0.202	16.9	0.52	Weak	13
	M2	12–20	8	0.211	18.6	0.51	Weak	13
	Ha1	20–35	4	0.173	19.8	0.42	Initial	13
	Ha2	35–50	5	0.132	16.3	0.41	Initial	8.5
	Ha3	50–80	8	0.284	30.2	0.49	Weak	3
E	Ha1	0–20	9	0.185	23.3	0.61	Moderate	8.5
	Ha3	20–30	3	0.223	32.9	0.52	Weak	3
	Ha4	30–41	3	0.277	46.5	0.54	Weak	3
	Ha5	41–49	3	0.301	52.4	0.53	Weak	0

RF = rubbed fibre content, BD = bulk density, W_1 = water holding capacity index, MED = concentration of ethanol solution percolates less than 3 seconds. Soil horizon symbols: Hi = slightly decomposed peat, He = moderately decomposed peat, Ha = highly decomposed peat, M = moorsh.

Soil water repellency and state of secondary transformation

The MED test classified the vast majority of the soil samples as very strongly or extremely hydrophobic (Table 3). Particularly strong water repellency was observed in the weakly to moderately decomposed peat soil horizons of Profiles A and B (significant positive correlation, r = 0.590) (Table 4). The peat from spring fens (Profiles D and E) was moderately to very hydrophilic (Table 3), with the strongest water repellency in the moorsh horizons M1 and M2 of Profile D.

The values of W_1 index (state of secondary transformation) ranged from 0.27 to 0.72 (Table 3). The lowest values were recorded in Profiles A and B (raised bogs). Apart from Horizon Ha2 in Profile B (0.72), all of the soil samples were placed in the initial, weak and moderate classes of secondary transformation. In transitional bog (Profile C) and fen peatland (Profiles D and E), the values of W_1 index were relatively constant throughout the soil profiles. The range of values (0.41–0.54) observed in Profiles D and E was particularly narrow, allowing these soils to be classified as initially or weakly secondary transformed (Table 3). Statistical analysis showed significant negative correlation (r = -0.508) between W_1 index and TOC content (Table 4), especially for Plots C, D and E, which was confirmed by the results of PCA analysis (Figure 2).

Chemical properties

TOC content was in the range 169–493 g kg^{-1}. It was the lowest in the soil horizons with the highest admixture of mineral material, and 2–3 fold higher than in "pure" organic horizons (Table 5). The fen soils (Plots D and E) had lower organic carbon content than raised bog peat (Figure 3). In contrast, the highest total nitrogen content (TN) was observed in Profile D, and the lowest in Profile B (Table 5). The TOC/TN quotient, which is used as an indicator for the mineralisation of organic matter, showed high variability among the study sites and ranged from 14.6 to 40.5. The lowest ratios (< 20) were observed in Profile D, and fairly similar values were recorded for Profile E. In the raised bogs (Profiles A and B) TOC/TN was definitely higher than previously reported, indicating weak mineralisation of these soils (Table 5). Humification index based on the absorbance ratio Q_4/Q_6 ranged from 3.10 to 10.6 (Table 5). The lowest ratios were recorded in Profiles B and D, and the highest in Profiles A and C. Values of Q_4/Q_6 showed significant positive correlation only with HWC, which is the potentially labile form of carbon (Table 4). HWC concentrations ranged from 0.50 to 4.69 g kg^{-1} (Table 5). Excluding the result for the topsoil horizon Ha 1 (2.50 g kg^{-1}), the highest HWC concentration was found at Plot A and the lowest at Plot E. The values of CWC were decidedly lower than those of HWC and ranged between 0.04 g kg^{-1} and 0.67 g kg^{-1}. The mean HWC and CWC concentrations showed similar tendencies, both being the highest in topsoil horizons and lowest mostly in the bottom parts of the profiles (significant negative correlation with depth, Table 4). The principal component analysis (PCA) showed that larger quantities of potentially labile organic carbon (HWC) were present in the raised bog soils (Plots A and B) (Figure 3).

Table 4. Pearson coefficients for soil properties (n = 69). For explanations of symbols see Tables 3 and 5.

	MED	CWC	HWC	TOC/TN	W_1
Depth	-0.176	-0.617*	-0.595*	-0.086	-0.042
Ash	-0.140	-0.657*	-0.656*	-0.106	0.340
RF	0.590*	0.468*	0.561*	0.751*	-0.505*
BD	-0.365	-0.610*	-0.632*	-0.321	0.477*
TOC	0.551*	0.277	0.399	0.414*	-0.508*
Q_4/Q_6	0.232	0.115	0.466*	0.268	0.268

Explanation: * = significant at $p < 0.05$.

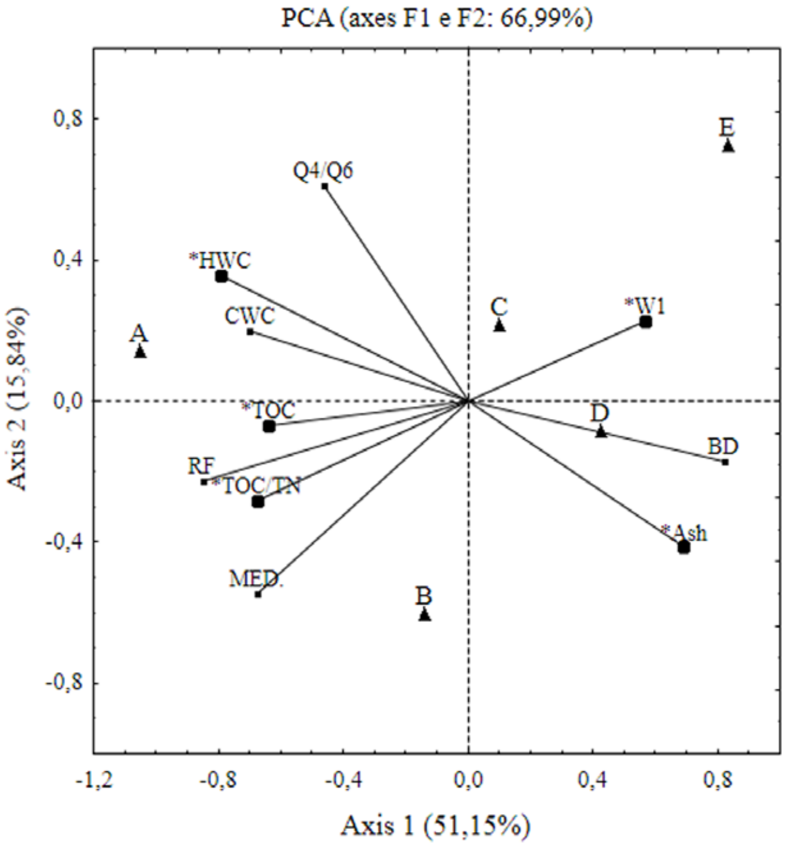

Figure 2. Principal component analysis (PCA) among soil parameters and study sites. Explanations of symbols as in Tables 3 and 4.

DISCUSSION

The alternating occurrence of differently decomposed organic material in the peat bog profiles (A and B) may indicate periodic changes of hydrological conditions, as described by other authors (e.g. Kabała *et al.* 2011, Bogacz *et al.* 2012, Brouns *et al.* 2014). Moreover, peat subsidence in the afforested peatlands resulted in changes of the soil physical properties, e.g. bulk density and ash content (Prévost *et al.* 1999). However, despite the long-term artificial drainage of peatlands in the Stołowe Mountains, we found that the moorsh material which characterises drained organic soils occurred only in the topsoil of Profile D. This confirms previous observations that organic soils at fen peatlands are more susceptible to transformation than bog soils (Sokołowska *et al.* 2005), as also shown by the cluster analysis in the present study (Figure 2). Soil water repellency status analysis (MED) showed that the investigated soils consisted mainly of hydrophobic organic material. The hydrophobic character of surface moorsh horizons in Profile D may be caused by colloidal organic compounds susceptible to coagulation. This suggestion is supported by the low Q_4/Q_6 ratio, as also reported by Matyka-Szarzyńska & Sokołowska (2005). On the other hand, the strong hydrophobicity of organic soils from raised bogs was particularly determined by the high contents of weakly decomposed fibre and organic matter, as confirmed by statistical analysis (Table 4). These conclusions are in line with the findings of other authors, e.g. Berglund & Persson (1996) and Łachacz *et al.* (2009). The weakly decomposed fibres of peat-forming plants are strongly hydrophobic after desiccation, which reinforces soil water repellency (Huffman *et al.* 2001, DeBano 2000). The initial or weak state of secondary transformation, observed even in the moorsh horizons, may indicate that long-term forestry drainage has affected the studied soils to only a minor degree. The intensity of drainage might be weakened by soligenous water supplies (Bujang *et al.* 2014), which are known to be present in the Stołowe Mountains (Glina *et al*. 2016a). The lack of recent drainage network maintenance may also be a pertinent factor (Kabała *et al.* 2011, Bogacz *et al.* 2012). The surprising W_1 index (moderate state of secondary transformation) we obtained for the basal

Table 5. Chemical properties of the soil horizons in Profiles A–E (mean values from three replicates, n = 69).

Profile	Soil horizon	Depth (cm)	TOC	TN	CWC	HWC	TOC/TN	Q_4/Q_6
			(g kg^{-1})					
A	Hi1	0–10	450	11.5	0.62	4.69	39.1	10.6
	He	10–19	472	16.1	0.40	2.51	29.3	9.08
	Hi2	19–34	476	13.9	0.34	2.14	34.3	7,58
	Ha	34–37	484	15.8	0.38	2.41	30.7	6.05
	Hi3	37–54	493	14.9	0.31	1.98	33.1	7.68
B	Hi1	0–9	346	10.5	0.67	2.90	32.9	4.81
	Ha1	9–18	176	6.70	0.23	1.02	26.5	4.48
	Hi2	18–33	436	10.8	0.32	1.66	40.5	4.20
	Hi3	33–40	431	11.6	0.27	1.61	37.2	4.67
	Ha2	40–47	260	9.71	0.18	0.91	26.8	4.40
C	Ha1	0–8	402	12.9	0.32	1.91	31.1	7.66
	Ha2	8–14	392	15.4	0.45	2.58	25.5	7.57
	Ha3	14–23	369	13.2	0.27	1.35	27.9	7.74
	Ha4	23–32	169	8.81	0.19	0.94	19.2	5.76
D	M1	0–12	398	27.3	0.65	3.42	14.6	3.13
	M2	12–20	395	26.7	0.43	1.39	14.8	3.53
	Ha1	20–35	408	27.6	0.23	0.83	14.8	3.52
	Ha2	35–50	424	24.4	0.27	1.05	17.4	4.09
	Ha3	50–80	345	16.1	0.26	1.02	21.4	3.10
E	Ha1	0–20	387	16.6	0.36	2.50	23.3	8.28
	Ha2	20–30	263	12.2	0.21	0.98	21.5	6.69
	Ha3	30–41	271	13.4	0.09	0.82	20.2	6.52
	Ha4	41–49	244	11.9	0.04	0.50	20.5	5.98

Explanation: TOC = total organic carbon, TN = total nitrogen, HWC = hot water extractable carbon, CWC = cold water extractable carbon, Q_4/Q_6 = humification index.

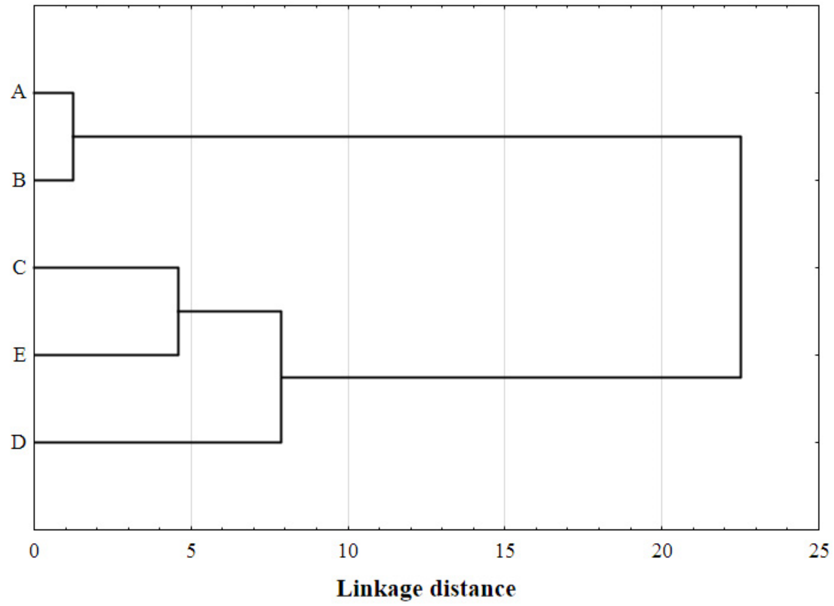

Figure 3. Cluster analysis - Ward's method with Euclidean distance.

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part of Profile B (raised bog) might be explained by the presence of macroscopic charcoals in this layer. It has been reported that fire can create a highly water repellent soil layer rich in hydrophobic organic compounds (DeBano 2000). The peatland soils studied here are definitely at an earlier stage of secondary transformation than degraded soligenous peatlands in lowland areas that have been drained since the 1950s or 1960s (e.g. Matyka-Szarzyńska & Sokołowska 2005, Sokołowska *et al*. 2005, Kalisz *et al*. 2010, Kalisz *et al*. 2015, Glina *et al*. 2016b). Temporary desiccation of the surface soil horizons investigated here was confirmed both by the W_1 values and by their higher HWC and CWC concentrations. Variations in HWC values reflect differences in microbial activity (Kalisz *et al*. 2015), while easily mineralisable carbon (CWC) indicates the potential intensity of actual DOC fluxes in drainage water (Worall *et al.* 2007). Degraded organic soils that are resistant to rewetting have lost their ability to support globally important processes such as carbon sequestration (Strack *et al.* 2008). The lowest TOC/TN ratio observed in the soil profiles (D and E) at fen peatlands of the Skalniak ridge might indicate temporary drying of these soils, which accelerates the mineralisation of organic matter. Although the low TOC/TN value for Profile D may have been caused by drainage, it is more likely to arise from the botanical composition of this (*Alnus*) peat (Glina 2014). *Alnus* trees are known for their ability to fix large amounts of nitrogen (Selmants *et al.* 2005), which would result in a lower TOC/TN ratio. On the basis of our results it could be stated that forestry drainage of peatlands in the Stołowe Mountains during the last century has caused severe changes, mainly in the morphology of their soils (e.g. peat thickness, degree of peat decomposition). However, although present-day water conditions (Table 1) cannot support peat accumulation, the soils investigated here show rather minor impacts arising from the now derelict drainage networks. Most of these soils exhibited evidence of the initial stages of transformation processes, reflected by only weak mineralisation of organic matter. The exceptions were the soils in fen peatlands on the Skalniak ridge, where stronger transformation was evidenced by soil physicochemical and chemical properties as well as by the moorsh-forming process. In the raised bog and transitional mire soils, long-term drainage and forest management had mainly transformed organic matter in surface soil horizons, where enhanced aeration contributed to increased content of labile carbon forms (CWC and HWC). Further drying of these soils will negatively affect their ability to rewet. In order to limit further transformation and loss of organic matter from these peatlands, drainage ditches should be blocked forthwith. Furthermore, some of the trees in priority (central) areas should be eliminated by ring-barking or felling in order to reduce evapotranspiration.

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REFERENCES

Benavides, J.C. (2014) The effect of drainage on organic matter accumulation and plant communities of high-altitude peatlands in the Colombian tropical Andes. *Mires and Peat*, 15, 1–15.

Berglund, K. & Persson, L. (1996) Water repellency of cultivated organic soils. *Acta Agriculturae Scandinavica*, 46, 145–152.

Bogacz, A., Dzięcioł, D., Glina, B. & Gersztyn, L. (2012) Peat soils in the restoration Niknąca Łąka peatland in the Stołowe Mountains National Park. *Soil Science Annual*, 63(2), 3–8.

Bogacz, A. & Glina, B. (2015) Distribution, age and transformation of organic soils in the Sudety Mountains In: Kabała, C. (ed.), *Soils of Lower Silesia: Origin, Diversity and Protection*. PTG, PTSH, Wrocław, 225–234.

Bojko, O. & Kabala, C. (2015) Loss-on-ignition as an estimate of total organic carbon in the mountain soils. *Polish Journal of Soil Science*, 47, 71–79.

Brouns, K., Verhoeven, J.T.A. & Hefting, M.M. (2014) Short period of oxygenation releases latch on peat decomposition. *Science of the Total Environment*, 481, 61–68.

Bujang, B.K.H., Arun, P., Afshin, A. & Sina, K. (2014) *Geotechnics of Organic Soils and Peat*. CRC Press, Boca Raton, USA, 265 pp.

Chen, H.Q., Hou, R.X., Gong, Y.S., Li, H.W., Fan, M.S. & Kuzyakov, Y. (2009) Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. *Soil and Tillage Research*, 106, 85–94.

DeBano L.F. (2000) Water repellency in soils: a historical overview. *Journal of Hydrology*, 231–

232, 4–32.

Doerr, S.H. (1998) On standardizing the 'Water Drop Penetration Time' and the 'Molarity of an Ethanol Droplet' techniques to classify soil hydrophobicity: a case study using medium textured soils. *Earth Surface Processes and Landforms*, 23, 663–668.

Gałka, B., Łabaz, B., Bogacz, A., Bojko, O. & Kabala, C. (2014) Conversion of Norway spruce forests will reduce organic carbon pools in the mountains soils of SW Poland. *Geoderma*, 213, 287–295.

Gawlik, J. (2000) Division of differently silted peat formations into classes according to their state of secondary transformations. *Acta Agrophysica*, 26, 17–24.

Glina, B. (2014) Spatial variability of the shallow organic soils in the Stołowe Mountains as a result of anthropogenic transformations. Doctoral thesis, Wrocław University of Environmental and Life Sciences, Wrocław, Poland, 208 pp.

Glina, B., Bogacz, A. & Woźniczka P. (2016a) Nitrogen mineralization in forestry drained peatland soils in the Stołowe Mountains National Park (Central Sudetes Mts). *Soil Science Annual*, 67(2), 64–72.

Glina, B., Gajewski, P., Kaczmarek, Z., Owczarzak, W. & Rybczyński, P. (2016b) Peatland soils degradation as an effect of long-term drainage - preliminary results of peatland ecosystems investigation in the Grójecka Valley (Central Poland). *Soil Science Annual*, 67(1), 1–7.

Heller, C. & Zeitz, J. (2012) Stability of soil organic matter in two northeastern Germany fen soils: the influence of site and soil development. *Journal of Soil and Sediments*, 12, 1231–1240.

Holden, J., Gascoign, M. & Bosanko, N.R. (2007) Erosion and natural revegetation associated with surface land drains in upland peatlands. *Earth Surface Processes and Landforms*, 32, 1547–1557.

Huffman E.L., MacDonald, L.H. & Stednick, J.D. (2001) Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. *Hydrological Processes*, 15, 2877–2892.

Ilnicki, P. & Zeitz, J. (2003) Irreversible loss of organic soil functions after reclamation. In: Parent, L.E. & Ilnicki, P. (eds.) *Organic Soils and Peat Materials for Sustainable Agriculture*. CRC Press, Boca Raton, USA, 15–32.

Jahn, R., Blume, H.P., Asio, V.B., Spaargaren, O. & Schad, P. (2006) *Guidelines for Soil Description*. FAO, Rome, 97 pp.

Kabała, C., Chodak, T., Bogacz, A., Łabaz, B., Jezierski, P., Gałka, B., Kaszubkiewicz, J. & Glina, B. (2011) Spatial variability of soils and habitats in the Stołowe Mountains. In: Chodak, T. (ed.) *Geo-ecological Conditions of the Stołowe Mountains National Park*. Wind, Wroclaw, Poland, 141–167 (in Polish with English abstract).

Kalisz, B., Łachacz, A. & Głażewski, R. (2010) Transformation of some organic matter components in organic soils exposed to drainage. *Turkish Journal of Agriculture and Forestry*, 34, 245–256.

Kalisz, B., Łachacz, A. & Głażewski, R. (2015) Effects of peat drainage on labile organic carbon and water repellency in NE Poland. *Turkish Journal of Agriculture and Forestry*, 39, 20–27.

Laik, R., Kumar, K., Das, D.K. & Chaturvedi, O.P. (2009) Labile soil organic matter pools in a calciorthent after 18 years of afforestation by different plantations. *Applied Soil Ecology*, 42, 71–78.

Landgraf, D., Leinweber, P. & Makeschin, F. (2006) Cold and hot water extractable organic matter as indicators of litter decomposition in forest soils. *Journal of Plant Nutrition and Soil Science*, 169, 76–82.

Lynn, W.C., McKinzie, W.E. & Grossmann, R.B. (1974) Field laboratory test for characterization of Histosols. In: Stelly. M. (ed.) *Histosols: Their Characteristics and Use*, SSSA Special Publication 6, Medison, 11–20.

Łabaz, B., Gałka, B., Bogacz, A., Waroszewski, J. & Kabala, C. (2014) Factors influencing humus forms and forest litter properties in the mid-mountains under temperate climate of southwestern Poland. *Geoderma*, 230–231, 265–273.

Łabaz, B. & Kabala, C. (2016) Human-induced development of mollic and umbric horizons in drained and farmed swampy alluvial soils. *Catena*, 139, 117–126.

Łachacz, A., Nitkiewicz, M. & Kalisz, B. (2009) Water repellency of post-boggy soils with a various content of organic matter. *Biologia*, 64(3), 634–638.

Łajczak, A. (2013) Role of land relief and structure in the formation of peat bogs in mountain areas, as exemplified by the Polish Carpathians. *Landform Analysis*, 22, 61–73.

Matyka-Szarzyńska, D. & Sokołowska, Z. (2005) Physichemical properties of mucks at different stages of secondary transformation. *Acta Agrophysica*, 123, 68 pp.

Minkkinen, K. & Laine, J. (1998) Effect of forest drainage on the peat bulk density of pine mires in

Finland. *Canadian Journal of Forest Research*, 28, 178–186.

Moody, D.R. & Schlossberg, M.J. (2010) Soil water repellency index prediction using the molarity of ethanol droplet test. *Vadose Zone Journal*, 9, 1046–1051.

Paavilainen, E. & Päivänen, J. (1995) *Peatland Forestry: Ecology and Principles*. Springer Verlag, Berlin, Germany, 243 pp.

Prévost, M., Plamondon, A.P. & Belleau, P. (1999) Effects of drainage of a forested peatland on water quality and quantity. *Journal of Hydrology*, 214, 130–143.

Sapek, B. & Sapek, A. (1997) Methods for chemical analysis of organic soils. IMUZ, Faleny, 80 pp. (in Polish).

Sallantaus, T. (1995) Leaching in the material balance of peatlands - preliminary results. *Suo*, 43, 253–358.

Selmants, P.C., Hart, S.C., Boyle, S.I. & Stark, J.M. (2005) Red alder (*Alnus rubra*) alters community-level soil microbial function in conifer forests on the Pacific Northwest, USA. *Soil Biology and Biochemistry*, 37, 1860–1868.

Sienkiewicz, J. & Wójcik, G. (2012) *Plan ochrony Parku Narodowego Gór Stołowych - operat ochrony ekosystemów torfowiskowych* (*Protection Plan for the Stołowe Mountains National Park - Protection of Peatland Ecosystems*). Institute of Environmental Protection - National Research Institute, Warsaw, Poland, 24 pp. (in Polish).

Sokołowska, Z., Szajdak, L. & Matyka-Sarzyńska, D. (2005) Impact of the degree of secondary transformation on acid-base properties of organic compounds in mucks. *Geoderma*, 127, 80–90.

Sparling, G., Vojvodic-Vukovic, M. & Schipper, L.A. (1998) Hot-water-soluble C as a simple measure of labile soil organic matter: the relationship with microbial biomass C. *Soil Biology and Biochemistry*, 30, 1469–1472.

Stark, L. (1936) Zur Geschichte der Moor und Wälder Schlesiens in postglazialer Zeit (The history of the marshes and forests of Silesia in post-glacial times). *Botanische Jahrbücher*, 67, 494–640 (in German).

Strack, M., Waddington, J.M., Bourbonniere, R.A., Buckton, E.L., Shaw, K., Whittington, P. & Price, J.S. (2008) Effect of water table drawdown on peatland dissolved organic carbon export and dynamics. *Hydrological Processes*, 22(17), 3373–3385.

Wojewoda, J., Bialek, D., Bucha, M., Głuszyński, A., Gotowała, R., Krawczewski, J. & Schutty, B. (2011) Geology of the Góry Stołowe National Park. In: Chodak, T. (ed.) *Geo-ecological Conditions of the Stolowe Mountains National Park*. Wind, Wroclaw, Poland, 53–96 (in Polish with English abstract).

Worall, F., Armstrong, A. & Holden, J. (2007) Short-term impact of peat-drain blocking on water colour, dissolved organic carbon concentration, and water table depth. *Journal of Hydrology*, 337, 315–325.

WRB (2015) *World Reference Base for Soil Resources 2014, Update 2015*. International Soil Classification System for Naming Soil and Creating Legends for Soil Maps, IUSS Working Group, Food and Agriculture Organization of the United Nations, Rome, 190 pp.

Wüst-Galley, C., Mössinger, E. & Leifeld J. (2016) Loss of the soil carbon storage function of drained forested peatlands. *Mires and Peat*, 18(07), 1–22.

Yallop, A.R. & Clutterbuck, B. (2009) Land management as a factor controlling dissolved organic carbon release from upland peat soils 1: Spatial variation in DOC productivity. *Science of the Total Environment*, 407, 3803–3813.

Zhang, J.B., Song, C.C. & Wang, S.M. (2007) Dynamics of soil organic carbon and its fractions after abandonment of cultivated wetlands in Northeast China. *Soil and Tillage Research*, 96, 350–360.

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