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Effect of spruce swamp forest drainage and restoration on soil organic matter quality

Diplomová práce

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Master thesis

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Annotation The aim of the study was to determine the effect of spruce swamp forest drainage and water regime restoration on soil organic matter (SOM) quality. Six localities of spruce swamp forests in Šumava Mountains were studied (2 drained, 2 restored and 2 pristine). SOM quality was affected by long-term drainage. Spruce swamp forest restoration (3-7 years) did not have significant effect on SOM quality although other parameters (pH, bulk density, water level, plant coverage) changed.

This thesis is written in manuscript form and it will be submitted in journal Soil use and management, Wiley online library.

I hereby declare that I have worked on my diploma thesis independently and used only the sources listed in the bibliography.

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All soil extractions, measurements and data evaluation were done by me, except analyzes of samples on LiquiTOC for total C and N which were done by Daniel Vaněk, analyzes of dissolved forms of nitrogen and phosphorus on FIA done by Terezia Říhová, data of basic soil parameters provided by Zuzana Urbanová.

List of abbreviations

C	**Carbon**
CW	**Cold water extractable organic matter**
CW C	**Cold water extractable carbon**
CW N	**Cold water extractable nitrogen**
DOM	**Dissolved organic matter**
HAE	**Hot acid extractable organic matter**
HAE C	**Hot acid extractable carbon**
HAE N	**Hot acid extractable nitrogen**
HW	**Hot water extractable organic matter**
HW C	**Hot water extractable carbon**
HW N	**Hot water extractable nitrogen**
IR	**Infrared spectroscopy**
N	**Nitrogen**
NON	**Non-hydrolysable organic matter**
NON C	**Non-hydrolysable carbon**
NON N	**Non-hydrolysable nitrogen**
P	**Phosphorus**
SSF	**Spruce swamp forests**
SOM	**Soil organic matter**

Content

Introduction

Peatlands cover 3% of Earth's land surface and store a third of soil carbon (Joosten & Clark, 2002). They are mostly located in boreal zone (Strack, 2008), but islands of boreal nature are also found especially in mountains of temperate zone. However, they are also source of greenhouse gases. Wetlands produce nearly 50% of methane (CH_4) global emissions and they also produce low amount of nitrous oxide (N_2O) (Kirk, 2004).

SSF are unique ecosystems, which are found around springs. They are fed by underground water and the forest floor is dominated by hydrophilic species. Water level is close to soil surface for most of vegetation season. Nutrients content in soil is higher than in bogs which are fed only by precipitation. These ecosystems have properties of both bogs and mountain spruce forest. Trees and *Sphagnum* mosses accumulate peat and retain soil water. Many rare species of plants are found in these ecosystems. In boreal zone, these ecosystems are quite often, but large areas of SSF were drained in the past (mostly for forestry). Drainage causes increase of productivity of trees and the ecosystem changes to typical forest ecosystem. It affects vegetation, microbial activities, quality of SOM, DOM leaching and nutrients mobilization. However, drained peatlands can be restored. Hydrological restoration should return pristine peatlands functions to the disturbed ecosystem (Lode, 2001). For successful peatland restoration is essential water table recovery. This is precondition for peat- forming *Sphagnum* mosses and sedges (Tuittila et al., 2000; Kivimäki et al., 2008). The effect of SSF drainage and restoration on DOM has been rarely studied, although their response to changes in their hydrology is key factor for predicting potential influencing of the global C and N cycle.

Soil organic matter quantity and quality belong to the most important parameters affecting soil physico-chemical properties. Drainage of peatlands causes oxygenation of soil profile, change in soil microbial community composition and increase of decomposition of SOM. It results in decrease of total SOM content and change of SOM quality. At the same time, nutrients are released from decomposed SOM and thus eutrophication of the site may be a problem. These changes of soil properties and physic-chemical conditions lead to significant change of type of vegetation and its function which again affects soil properties and functioning deeply. Water regime restoration of SSF should bring back the functions of the ecosystem. My thesis is focused on effect of SSF drainage and restoration on SOM quality and nutrients content in soil. I used simple fractionation methods. Acid hydrolysis is able to determine the labile from recalcitrant SOM pools. Water soluble organic matter (CW) and hot-water extractable organic matter (HW) are sensitive indicators of effects of changes in land use on DOM (Gregorich et al., 1994). CW and HW are labile pools of SOM and they are the main energy sources for microbial community.

Hypotheses:

1/ SSF drainage leads to the enhanced soil organic matter mineralization rate, because of increased aeration of upper soil layer. In short-term, leaching of DOM and nutrients out from the ecosystem is increased. Later, drainage leads to the changes in vegetation towards to the forest ecosystem. Lower soluble C and N pools ration and higher proportion of non-hydrolysable C pool will be found on the drained sites as compared to the pristine ones.

2/ SSF rewetting leads to the anoxic condition and to the decrease of redox potential in soil, later vegetation is also changed. Enhanced water table causes dying of the vegetation adapted to the drier conditions and part of microbial community. DOM and mineral nutrients will be released (leached) from dead microbial and plant biomass. Higher soluble C and N pools and mineral nutrients (N and P) concentrations will be found on restored sites than on pristine ones, due to dying of tree canopy.

The aims of study

The main aim of the study was to determine the effect of spruce swamp forest drainage and water regime restoration on soil organic matter quality.

Further aims were 1/ to determine if soil organic matter quality is affected in different way in upper (0-10 cm) and lower (10-30cm) soil layers after spruce swamp forest drainage and water regime restoration and 2/ to determine the effect of the distance from the drainage ditch on soil organic matter quality.

Review

Nutrients cycles in peatlands

Most of the carbon in peatlands is the product of photosynthesis mainly by plants and also by algae (van der Valk, 2006). Peatlands can accumulate several metres of undecomposed peat over thousands years. The water table level is a crucial factor controlling rate of decomposition. It causes anoxic condition and it influences redox potential which is decreasing with depth (Rydin & Jeglum, 2006). CH_4, CO_2 and partially decomposed and humified residues are products of anaerobic decomposition of organic matter (Kirk, 2004). There are some C losses from the peatland ecosystem by respiration (Kirk, 2004; Rydin & Jeglum, 2006), by methane emission, by dissolved inorganic carbon and dissolved organic matter (DOM) that is leached from the ecosystem (Rydin & Jeglum, 2006).

Peatlands have the widest range of redox conditions of any ecosystem and therefore they have important role in global nitrogen (N) cycle (Kirk, 2004). Nitrogen is present in peatlands in organic forms (dissolved and particular forms), in inorganic dissolved forms (ammonium N (NH_4^+), nitrite N (NO_2) and nitrate N (NO_3^-)) and in gaseous forms (N_2, N_2O etc.). N is the most often limiting nutrient in peatlands (Reddy & DeLaune, 2008). The most important reactions in wetlands N cycle are N fixation, immobilization, ammonification, nitrification and denitrification. Worldwide, 20% of natural N_2 fixation takes place in wetlands (Kirk, 2004). When ammonification-immobilization cycle is stable, it results in a stabilized C:N ratio of the organic matter. A wider C:N ratio elevate immobilization, whereas the narrower ratio promote mineralization. Nitrification in peatlands runs in aerobic conditions. Nitrification reaction supports denitrification bacteria with nitrates (Reddy & DeLaune, 2008). Denitrification runs in anoxic conditions and it permanently removes N from the ecosystem (van der Valk, 2006). The peatlands are very suitable for an anaerobic ammonium oxidation process (Zhu et al., 2010).

P is found in peatlands in inorganic form (orthophosphate) and in organic form (van der Valk, 2006). Vegetation is a main source of organic phosphorus in peatlands. Organic P is mineralized by biotic processes in peatlands. In peatlands, P is transported in soluble and particulate forms and it is retained by surface adsorption on minerals and organic particles, precipitation, microbial immobilization, plant uptake and sequestering (Reddy & DeLaune, 2008).

Pristine peatlands

In pristine peatlands, net primary production is higher than decomposition. Accumulated organic matter is peat (Korhola et al., 1995). Development of peat humus layer is related to high C:N ratio (Pilkington et al., 2005). *Sphagnum* mosses are dominant species of the ground cover and they are important for accumulation of organic matter in boreal peatlands (Gunnarsson, 2005).

In SSF, both wetland and forest species occur. These sites combine both peatland and forest ecosystem elements (Hörnberg et al., 1998). These forests have usually water table near to the surface, low soil temperature (Lieffersand & Rothwell, 1987), poor aeration (Campbell, 1980) and low nutrient availability (Tilton, 1978). Because of these conditions, the SSF productivity is generally low (Prevost et al., 1999).

Drained peatlands

Peatlands are drained for forestry, agriculture and peat mining for fuel (Chapman et al., 2003). Drainage for forestry is common in Fennoscandia and former USSR (Paavilainen & Päivänen, 1995). Nutrient rich peatlands, including SSF, was drained first and most intensively (Hånell, 1988).

Generally, drainage increases aerobic decomposition, because of the lower water table (De Mars et al., 1996), and consequently higher fluctuation of water table (Holden et al., 2004; 2006a) and leaching of nutrients (Holden et al., 2004). The litter and peat decay rate increase (Minkkinen et al., 1999) and pH decrease (except of acidic low production sites), both of them due to higher aeration and decomposition (Laine et al., 1995). C in vegetation and net primary production increase after drainage, especially in the tree stand (Minkkinen et al., 1999). In the opposite, *Sphagnum* species coverage is decreasing (Laine et al., 1995). Water level is usually between >35 cm to >55 cm below the surface after drainage and trees transpiration cause further lowering of water table (Paavilainen & Päivänen, 1995). Increasing tree weight together with the tree roots assimilation of ions and higher decomposition cause soil compaction. In the long term, water table can slightly increase because of the soil compaction and SOM decomposition (Eggelsmann, 1986). All these factors are resulting in that peatlands vegetation can start succession to the forest vegetation (Laine & Vanha-Majamaa, 1992; Laine et al., 1995).

Peatlands drainage has both dual effects on greenhouse gases. CH_4 emissions are lower after drainage, but the ditches emit CH_4 at the similar rate as pristine peatland (Minkkinen, 1999). However, numerous studies, cited by van Arnold (2004) showed that N in drained peatlands becomes available for N_2O producing bacteria. Furthermore, drained organic soils are significant N_2O and CO_2 sources (Silvola et al., 1996a).

High nitrate NO_3^- concentrations in the porewater of drained peatlands are caused by aeration of the peat and subsequent decomposition and nitrification of organic nitrogen (Holden et al., 2004; Olde Venterink et al., 2002; Willison et al., 1998). Total N concentrations in the topsoil increase because of enhance N microbial immobilization (Wells & Williams, 1996). This also lead to decrease of C:N ratio (Holden et al., 2004). Conversely, mineralized organic P compounds can be sorbed to $Fe^{(III)}$-hydroxides and become temporarily immobilized (Zak et al., 2004). In short-term, the leaching of organic C increase (Zak et al., 2004), but in long-term organic C leaching is small (Sallantaus, 1994; Holl et al., 2009). In degraded peatlands, DOM concentration is low in pore water (Kalbitz et al., 2002).

Restored peatland

Peatland restoration should return pristine peatlands functions to the ecosystem (Lode, 2001). Water table recovery is essential for successful peatland restoration. This is precondition for spreading of peat-forming *Sphagnum* mosses and sedges (Tuittila et al., 2000; Kivimäki et al., 2008). Restoration, in short-term, rapidly rises water table and it changes peat chemistry (Tuittila et al., 1999; Jauhiainen et al., 2002; Worrall et al., 2007). Rewetting in forested peatland (including SSF) is more problematic (Kusler, 2006), because of the survival seedlings and mature trees (Kulser & Kentola, 1989; McLeod, 2000).

Olde Venterink (2002) found that N or dissolved organic N availability and N decomposition (Van Dijk et al., 2004) is not reduced after rewetting. However, rewetting significantly increase denitrification, P concentrations, mobilisation of P (Olde Venterink et al., 2002), P availability for plants (Chepkwony et al., 2001) and also DOM porewater concentrations in short-term (Kalbitz et al., 2002; Worrall et al., 2007; Waddington et al., 2008). Rewetting enhances respiration (Glatzel et al., 2003; Waddington et al., 2003; 2010) and emitting of CH_4 (Waddington & Day, 2007) because of enhanced DOM production or labile DOM quality. Only stable water table results in the lower DOM concentration. There are strong differences between short-term and long-term effects of rewetting (Holl et al., 2009).

SOM in peatlands

SOM is a complex of plant, microbial, and animal products (Reddy & DeLaune, 2008). According to Stevenson (1994) SOM can be divided into three groups: nonhumic, phenolic and humic substances. The largest fraction of SOM in forested peatlands originates in detrital organic matter from trees. Root exudation of organic compounds may be also important source of organic matter. Soil microorganisms represent another significant source of SOM to forested peatland soils (Reddy & DeLaune, 2008). Dissolved organic matter (DOM) is usually only 0,04-0,22% of the total SOM (Zsolnay, 1996).

Sources of DOM

DOM are plant-derived organic substances, which are transformed and modified by microorganisms (Guggenberger & Zech, 1993; Guggenberger et al., 1994a; McDowell et al., 1998; McDowell, 2003). DOM is SOM fraction, which passes through a 0,45mm filter (Herbert et al., 1993; Bolan et al., 1996; Zsolnay, 2003) and it is present in terrestrial and aquatic ecosystems (Bolan et al., 2011). DOM may originate from plant litter (Kalbitz et al., 2003; Hagedorn et al., 2004; Kiikkilä et al., 2006; Müller et al., 2009), soil humus (Kalbitz et al. 2000), microbial community (Williams & Edwards, 1993; Ghani et al., 2007; Steenwerth & Belina, 2008), soil animals or root exudates (Yano et al., 2000). DOM is mostly the end product of microbial metabolism (Bolan et al., 2011). Litter and humus are the most important DOM sources (Kalbitz et al., 2000). DOM originating from litterfall is more degradable than DOM which originates from humus layer (Kiikkilä et al., 2011). DOM concentrations decrease with soil depth (Kalbitz et al., 2000).

In forest, litterfall is the most important source of C (Gosz et al., 1976; Nordén, 1994). Root exudation is also significant source of DOM in forest, especially in coniferous forest (Strack et al., 2011). In forest soils, SOM mass is positively correlated with DOM leaching and CO_2 mineralization, so high decomposition promotes high DOM concentrations. Hydrologic conditions can be more important for DOM concentration than biotic controls (Kalbitz et al., 2000).

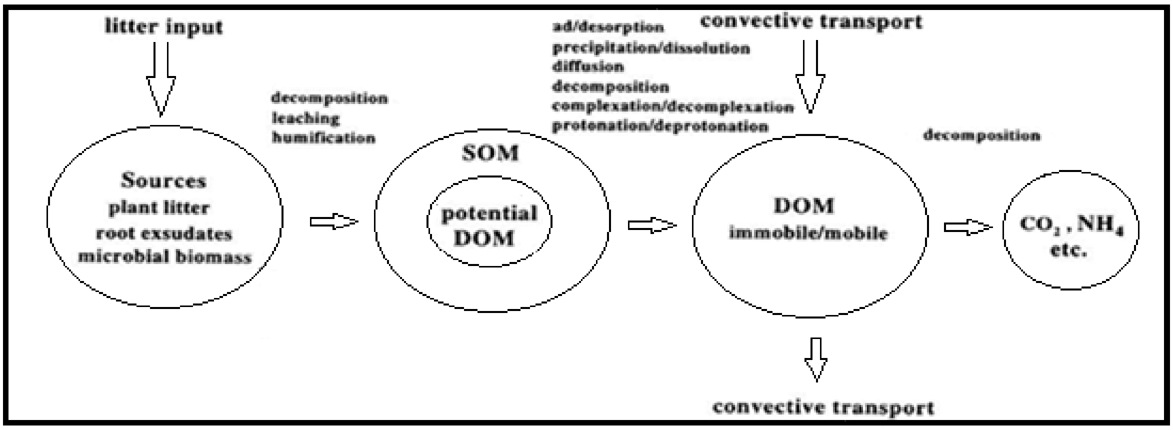

Figure 1: Conceptual model of the processes involved in the formation of DOM (modified from Kalbitz et al., 2000).

Quality of DOM

The quality of DOM has a key role in C and N cycle in forest soils (Marchner & Kalbitz, 2003). Size of dissolved molecules of organic matter is from simple amino acids to high molecular DOM (Neff & Asner, 2001). DOM may be the most important energy and nutrient source for microorganisms (Marchner & Kalbitz, 2003).

Marschner & Kalbitz (2003) divide DOM into labile DOM and recalcitrant DOM. Labile DOM are low molecular compounds like glucose, fructose, aminosugars, low molecular weight organic acids and proteins. Recalcitrant DOM are high molecular compounds like polysacharids, microbially derived degradation products and other plant compounds (Marschner & Kalbitz, 2003). These pools differ in mobility and lability (Chantigny, 2003; Strack et al., 2011).

The elementary composition of DOM depends on its origin (Bolan et al., 2011). Quality of litter play important role in controlling DOM concentration (Kuiters, 1993). Coniferous forest soils contain more DOM and dissolved organic N than hardwood forests (David & Driscoll, 1984; Cronan & Aiken, 1985; Currie et al., 1996), because conifer litter contains more recalcitrant DOM (Hongve et al., 2000; Kaiser et al., 2001; 2002; Kalbitz et al., 2003).

Transformation of DOM

DOM turnover is important to the C and N cycle (Kalbitz et al., 2000). DOM is the most mobile and actively cycling SOM fraction, although it is only small part of SOM. It influences and undergoes many of biogeochemical processes (fig. 1). DOM is a connecting factor in the mobilization and nutrient loss. DOM is transformed by microbial decomposition, photodegradation and adsorption (Bolan et al., 2011). DOM processes are influenced by both abiotic and biotic factors. Abiotic factors are pH, organic C content, clay content, temperature (Bolan et al., 2011), hydrological conditions (Kalbitz et al., 2000) and inhibitory compounds (Qualls and Richardson, 2003). Biotic factors are microbial activity (Bolan et al., 2011), the presence of plants and mycorrhizae (van Hees et al., 2003).

DOM is mainly by-product of decomposition (Bolan et al., 2011). High microbial activity and high fungi to bacteria ratio increase DOM concentrations in the soil, especially when soils conditions promote enhanced decomposition (Kalbitz et al., 2000). Soil fauna also increase DOM concentrations in soils by raising the microbial biomass turnover (Williams & Edwards, 1993). DOM can be an energy substrate for microbial processes (Bolan et al., 2011). 10 to 40% of DOM can be decomposed by microbes, so quality of DOM affects decomposition rate.

Soil organo-mineral complexes have a resistance to decomposition. Adsorption of DOM is one process of the formation of soil organo-mineral complexes on mineral particles (Bolan et al., 2011). Adsorption of DOM is the main process determining the retention of DOM in soils (Kalbitz et al., 2000). This process also controls the leaching of DOM (Kalbitz et al., 2000; Marschner & Kalbitz, 2003) and it can fractionate DOM (Kalbitz, 2001). DOM is adsorbed to metal ions such as Ca^{2+},Al^{3+},$Fe^{2+/3+}$ and clay minerals (Kalbitz et al., 2000). This adsorption can be affected by anions, because anions displace DOM form sorption sites with different strength (PO_3^{-4}> SO_2^{-4}>Cl^-) (Gu et al., 1994; Reemtsma et al., 1999). Complexation of heavy metals and metaloides (Cu, Pb, Hg, and Cd) (Bolan, 2011) and sorption are key regulators of trace metals concentrations in water systems (Kirk, 2004). The concentration of Cr, Hg and Cu is positively correlated with DOM (Kalbitz & Wennrichn, 1998). The majority of DOM is mineralized to CO_2 by microbial community and released (emitted) to the atmosphere Bolan et al., 2011). Generally, DOM quality controls the loss of C, N, and P from ecosystems and it has main role for CH_4 and N_2O production (Kiikkilä, 2011).

Influence of drainage and restoration on DOM dynamics

Peatlands are important source of DOM (Bolan et al., 2011). Peatland DOM processes and quality are related to water table position (Freeman et al., 1993; Moore et al., 2001). Peatlands drainage influences vegetation, microbial organisms, nutrients mobility, DOM quality and leaching (Kiikkila et al., 2006). It also enhances net DOM production (Glatzel et al., 2003) and increases DOM fluxes (Moore, 1998), because of enhanced runoff. It results in a significant increase in DOM loss (Waddington et al., 2008). The DOM retention is higher in intact peatlands than in degraded ones (Kalbitz, 2001). Drainage supports trees growth and in opposite, it harms *Sphagnum* moss species. This lead to the changes in litter input to the soil (Laiho et al., 2003) and consequently in DOM quality (Kiikkila et al., 2006). In poorly drained areas, DOM concentration in surface horizon of drained peatlands can be very high (Kalbitz et al., 2000).

Peatland restoration affects ecosystem hydrology due to ditch blocking and water table increase. This leads to changes in DOM production and quality. Many authors cited by Kalbitz et al. (2000) found that rewetting after dry period increase DOM concentrations. Dry period can cause accumulation of microbial products and this enhances DOM concentrations in the soil (Kalbitz et al., 2000). Concentrations of P and NH_4^+ also increase after rewetting of long-term drained peatlands (van Dijk et al., 2004; Zak et al., 2004; Tiemeyer et al., 2005). After rewetting, P, NH_4^+ and soil organic C mobilisation depend on degree of peat decomposition (Zak et al., 2007).

Manuscript

Effect of spruce swamp forest drainage and restoration on soil organic matter quality

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Keywords: DOM, fractionation, infrared spectroscopy, spruce swamp forests, restoration, drainage

Abstract

Six spruce swamp forests (SSF) with different disturbance history and management (pristine, drained and restored) were studied in Šumava National Park. The aim of the study was to analyse the effect of SSF management, i.e. drainage and restoration (re-wetting), on soil organic matter (SOM) quality. Pristine sites were used as a control. SOM quality was characterized by simple fractionation that included cold and hot water extractions and acid hydrolysis, and by infrared spectroscopy (IR). Management had significant effect on SOM quality. Drainage decreased the concentration of easily extractable soil pools and increased the concentration of non-hydrolysable pool (lignin and other recalcitrant compounds). Hot water extractable pool was shown as the most affected pool by management. Site restoration had only minor effect on SOM quality which still resembled that of the drained sites. Surprisingly, soluble C and N pools were the lowest on the restored sites, although we expected the highest concentrations of soluble C and N due to inputs of fresh litter from dying trees after site re-wetting. Our results indicate that longer period than 7 years is needed for change of SOM quality of previously drained SSF after their restoration.

Introduction

Peatlands cover 3% of Earth's land surface. They store up to a one third of all the terrestrial carbon (C) and thus affect global C cycle and climate changes (Vitt et al., 2000; Turunen et al., 2002). Peatland C sink function is sensitive to changes in environmental conditions (Bubier et al., 2003; Aurela et al., 2004; 2007; Roulet et al., 2007; Chivers et al., 2009).

Spruce swamp forests (SSF) combine both peatland and mineral soil forest ecosystems properties (e.g. Hörnberg et al., 1998). SSF are typicall of boreal landscape, but they are also found in temperate zone. SSF are unique ecosystems which support high biodiversity and rare plant and animal species, but large areas of SSF were drained mostly for forestry purposes. Similar to Nordic countries, most of peatlands in the Czech Republic were drained for agricultural and forestry purpose (70% of peatlands in the Sumava Mountains were drained especially for forestry).

Peatlands drainage accelerates soil C decomposition (Laiho, 2006) but net primary production and C accumulation in living plant biomass and plant litter usually increase (Minkkinen et al., 1999; Straková et al., 2012). Drainage of peatlands causes decrease of *Sphagnum* species coverage (Laine et al., 1995), subsidence of peat and increase of peat bulk density. Early studies of peatlands drained for forestry presupposed that these peatlands have positive net C balance in the soil due to increasing tree growth (Cannell & Dewar, 1995; Laiho & Finér, 1996; Laiho & Laine, 1997; Minkkinen & Laine, 1998). In opposite, recent studies suggest that net C balance in such sites is negative (Lapveteläinen et al., 2007). Lowering of water table leads to widening of upper aerobic zone that can be followed by high peat decay rates and consequently by increased production of DOM (Hribljan, 2012). Enhanced decomposition is mainly fuelled by DOM. This leaves behind the more refractory DOM components (Kalbitz et al., 2003). The DOM of drained peatlands contains a larger portion of aromatic compounds than the DOM of intact peatlands (Kalbitz et al., 2003). In long-term, low DOM concentration is usually found in pore water of drained and degraded peatlands (Kalbitz et al., 2002). Increase of total N concentrations in the topsoil (Wells & Wiliiams, 1996) can lead to decrease of C:N ratio of soil organic matter (Holden, 2004). Holden (2004), Olde Venterink (2002) and Willison (1998) also found high NO_3^- concentrations in the porewater after peatlands drainage.

Restoration of drained SSF should bring back their natural functions (Robert et al., 1999; Waddington et al., 2003). For successful peatland restoration water table recovery is essential. However, rewetting can reduce microbial production of DOM due to the anoxic environment (Hribljan, 2012). Rewetting in forested peatland (including SSF) is even more problematic (Kusler, 2006), because of the trees survival (Kulser & Kentola, 1989; McLeod, 2000). Rewetting also causes changes in peat chemistry (Tuittila et al., 1999; Jauhiainen et al., 2002; Worrall et al., 2007). In short term, DOM (many authors cited by Kalbitz et al., 2000; Kalbitz et al., 2002; Worrall et al., 2007; Waddington et al., 2008) and P (Olde Venterink et al., 2002) concentrations increase after rewetting of previously drained peatlands. Decomposition is limited under anaerobic conditions (Moore & Dalva, 2001; Jungkunst et al., 2008) and metabolites may accumulate (Mulholland et al., 1990). This can consequently cause higher DOM concentrations than DOM generated from metabolites under aerobic conditions.

The effect of SSF drainage and restoration on DOM has been rarely studied. Holl et al. (2009) studied the amounts and composition of DOM in fen 20 years after restoration. They found that stable water table near to the surface caused lower DOM levels than in moderately degraded fen. They postulated that unstable water table results in higher DOM concentration than in non-rewetted sites (Holl et al., 2009). Glatzel et al. (2003) studied concentrations and properties of DOM in natural, harvested, and restored peatlands in eastern Quebec. They observed that anaerobic condition support DOM release from soils. Authors also found that peat bog harvesting and restoration significantly influence DOM porewater concentrations (Glatzel et al., 2003). We hypothesized that higher proportion of non-hydrolysable C fraction and lower soluble C and N concentrations will be found on the drained sites as compared to the pristine ones. Higher concentrations of soluble C and N and mineral nutrients (N and P) will be found on restored sites than on pristine ones, due to dying of tree canopy.

The aim of our study was to evaluate the effect of SSF drainage and restoration on SOM quality and on DOM and nutrients mobilization in soil. The next aims were to determine the effect of management on SOM quality in upper and lower soil layer and to determine the effect of the distance from the drainage ditch on SOM quality.

Methods

Study sites

Six SSF with different disturbance history and management were chosen for peat sampling (Table 1). Two SSF were drained (D1, D2), two SSF were restored (R1, R2) and two SSF are pristine (P1, P2). All study sites are located in the Šumava National Park (Bohemian Forest), 49° N, 13° E, in the southern part of the Czech Republic (Fig. 2). The study sites are situated at an altitude of 1100 – 1200 m a.s.l. The climate is cold and humid with an annual temperature around 4°C and annual precipitation ca. 1200 mm (1961-1990, Czech Hydro-meteorological Institute).

The two drained SSF sites were drained before 1960s. R1 site was rewetted in 2008 and R2 site in 2004-2005 by blocking ditches by timber dams. Vegetation differed between the sites. Norway spruce (*Picea abies*) was the dominant tree at all sites. In pristine sites, *Eriophorum vaginatum* was dominant in herb layer. Shrubs (*Vaccinium uliginosum, V. myrtillus, V. vitis-idaea*), sedges (*Carex rostrata, C. nigra, C. echinata*) and some grasses (*Calamagrostis villosa*) can be present in these sites. *Sphagnum* mosses were dominant in moss layer. On the drained sites, *V. myrtillus* dominates close to the ditches, whereas sedges, feather mosses and sometimes *Sphagnum* spp. are dominating further from the ditches where water level is closer to soil surface. Considerable changes in vegetation were observed on restored sites in first years after restoration. Most of the trees died due to re-wetting. *Eriophorum vaginatum* started to appear in herb layer. In moss layer, *Sphagnum* mosses spread in the surroundings of dammed ditches.

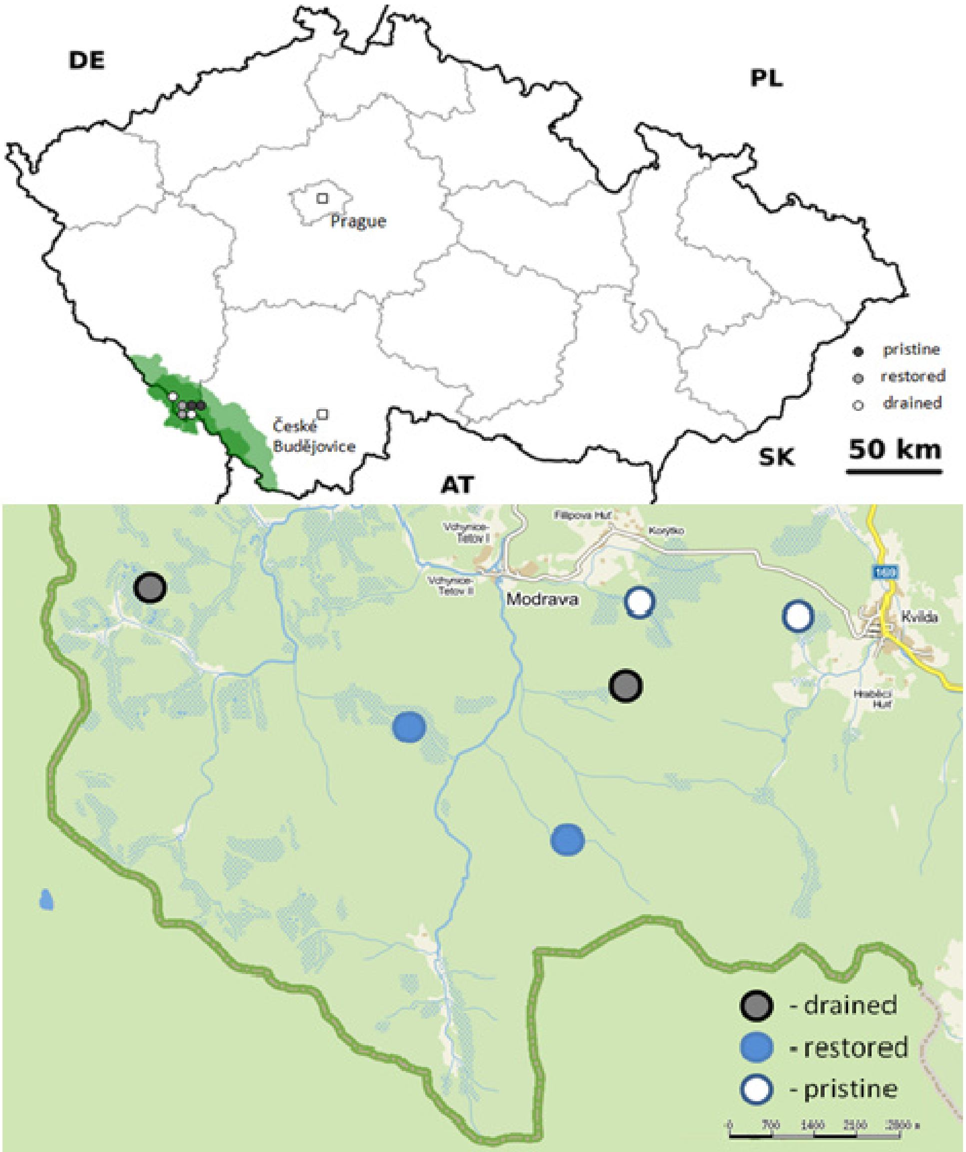

Figure 2 Study sites location.

Sample collection

Soil sampling was done in 12 July 2011 and 26 June 2012. Peat cores were taken by corer to the depth of 30 cm on each site. In case of drained and restored sites, two cores were collected near to the ditch (1m), two cores were taken from a distance of 10 meters from the ditch and last two cores were collected from a distance 20 meters from the ditch. We used the same sample collection pattern in pristine SSF. Pristine SSF sites were used as control sites. Soil cores were divided into two layers (0-10 cm and 10-30 cm) and all analyses were done separately for both layers in two replications.

Characterization of SOM quality

Homogenized (sieved) soil samples were placed in 150 ml plastic bottles and freeze-dried. Chemical fractionation was applied to all samples to separate DOM pools according to their mobility and availability. Freeze-dried samples were sequentially extracted with cold and hot water, and hot acid, leaving behind a non-hydrolysable residue fraction with slow turnover. Modified method from Uhlířová et al. (2007) was used. Briefly, the subsamples of 0.4 g (organic soils) or 0.2 g (peat soils) were undergone cold water extraction (CW). The samples were extracted by shaking in an end-over-end shaker with 30 ml of distilled water for 1 h at room temperature. After shaking, these samples were vacuum-filtered through a glass-fiber filter GF/F (0.45 mm) and frozen. This part of DOM is called water extractable organic matter (WEOM). CW extraction was done for both sample collections. The other extractions were done only for the first sampling collection.

The samples were re-extracted by 30 ml of hot water (80°C) for 18 h (Sparling et al. 1998), followed by vacuum filtration, and freezing of the filtrate. This part of extracted DOM is called hot water extractable organic matter (HW).

Inorganic N forms ($N–NO_3^-$, $N–NH_4^+$) and reactive phosphorus were measured in CW by flow-injection analyser (FIA Lachat QC8500, Lachat Instruments, USA). Filtrates from both CW and HW were analysed for total C and N contents by LiquiTOCII (Elementar, Germany).

Acid hydrolysis (6MHCl at 110°C for 18 h) was then applied on the dried and milled soil samples (1:10, soil to acid,) according to Leavitt et al. (1996). The non-hydrolysable soil fraction (NON) was retained on the glass-fibre filter GF/F (0.45 um). Chlorides were washed out with 100 ml of hot distilled water. The samples were dried at 105 °C and analysed for weight loss. Total C and N contents were measured by elementar analyser (Micro-cube elemental analyser (Elementar, Germany). The C and N contents of the acid-hydrolysed fraction were calculated as the difference between the C and N contents of the non-hydrolysable fraction and the sum of the C and N contents of both water extracts. All extractions of soil samples were carried out in two replicates. Total C and N contents were measured by elemental analyser on dried and milled soil samples before acid hydrolysis. Near infrared spectroscopy was used for analyses of total soil organic matter quality.

Infrared spectra were obtained with a Bruker VERTEX 70 series FTIR (Fourier Transform InfraRed) spectrometer (Bruker Optics, Germany) equipped with a horizontal ATR (Attenuated total reflectance) sampling accessory. Freeze-dried and powdered peat samples were inserted directly on the ATR crystal (without any dilution) and the MIRacle high-pressure digital clamp was used to achieve even distribution and contact of the sample and crystal. Each spectrum consisted of 65 averaged absorbance measurements between 4000 and 650 cm^{-1}, with 4 cm^{-1} resolution. Differences in the amplitude and baseline between different runs (samples) were corrected by standard normal variate transformation and de-trending (Barnes et al., 1989) using the Unscrambler software.

Definition of particular SOM fractions

The cold-water soluble material (CW) is composed of mono- and disaccharides, peptides, amino acids, amino sugars, phenols, fulvic acids, aliphatic and aromatic organic acids (Hagedorn et al., 2004). CWEOM contain little C derived from microbial biomass (van Ginkel et al., 1994).The majority of hot water extractable organic matter (HW) extract is composed of carbohydrates and mucigel of microbial origin (Haynes & Swift, 1990). However, microbial biomass is not more than 40% portion of the HW (Balaria, 2009). HWEOM contains substances such as carbohydrates, phenols, and lignin monomers. It contains more of these substances than CW, therefore HW may be the more bioavailable fraction (Balaria, 2009). HW can be considered as a labile SOM fraction. Acid hydrolysis by 6M HCl effectively dissolves young carbon compounds, leaving older molecules in the residue (Leavitt et al., 1996). It digests nitrogenous material (total protein) and partly also polysaccharides (Amelung et al., 1996).The NON fraction (soil residue after 6N HCl hydrolysis) contains mainly lignin and related compounds (Paul et al. 1997) and fats, waxes, resins and suberins (Rovira & Vallejo, 2002). The NON fraction is more resistant to decay compared to total SOM (Leavitt et al., 1996). It is biochemically more resistant SOM pool, which is depleted in carbohydrates and enriched in more stable and energy-rich compounds, such as alkyl (lipids) and aromatic C (Leifeld & Fuhrer, 2005).

Statistics

Multivariate analysis was conducted using Canoco 5 to distinguish influence of factors like management, soil layers, distance from ditches etc. and to show trends of chemical characteristics. Data were tested by redundancy analysis RDA, using all measured chemical characteristics (log-transformed) or infrared absorbance data as the response variables (centered and standardized) data and either management, soil layer (depth) or distance from ditches as the explanatory variables. The separated chemical characteristics were compared by hierarchic ANOVA (STATISTICA 10 for Windows) followed by post hoc comparison (unequal N HSD test). Hierarchic ANOVA were used separately for 0-10cm layer and for 10-30cm layer. This was based on the assumption that chemical characteristics can have different response in 0-10cm layer and in 10-30cm layer.

Results

Basic characteristics of study sites

The study sites differed in bulk density, pH and water table (Table 1). Bulk density was the highest on drained sites, and the lowest on pristine ones (n=2; F=32,6; $p<0.05$). Water table was decreasing in order: pristine > restored > drained sites (n=2; F=29; p <0,05). pH on both pristine and restored sites was higher than on drained sites (n=2; F=19; p<0,05). Total C and N did not differ between managements. *Sphagnum* and *Cyperaceae* species coverage was the highest on pristine site. Moss species other than *Sphagnum* coverage was the highest on drained sites and the lowest on pristine ones (Table 1).

Table 1 Basic characteristic of soil and vegetation from pristine (P1, P2), restored (R1, R2) and drained (D1, D2) spruce swamp forests. Soil parameters were measured in the layer 0-30 cm. Water table is low, due to extremely dry wetter. Data (except total C, total N and C/N ratio) were taken from Maanavilja et al. (submitted manuscript)

Study site	P1	P2	R1	R2	D1	D2
C-N ratio	28,5	37,6	31,3	28,1	27,2	38,4
Total N [%]	1,64	1,25	1,52	1,64	1,72	1,11
Total C [%]	46,39	45,66	46,78	45,12	45,56	42,09
pH	4,12	4,26	3,86	4,16	3,66	3,75
Bulk density [g cm-3]	0,049	0,064	0,091	0,105	0,156	0,118
Water table [cm]	-9,8	-15,1	-36,3	-39,8	-50,7	-68,9
Sphagnum [%]	82,2	90,0	53,3	46,2	33,5	49,2
Other mosses than *Sphagnum* [%]	13,3	4,3	28,3	24,2	37,5	30,8
Cyperaceae [%]	15,0	42,5	6,7	9,2	0,0	1,7
Shrubs_decid [%]	36,2	21,3	50,8	21,7	50,0	48,2
Shrubs_evergreen [%]	13,0	7,8	5,0	13,3	0,0	3,5

The proportion of SOM fraction

Table 2 C and N proportion for all fractions and C/N ratio from pristine (P1, P2), restored (R1, R2) and drained (D1, D2) spruce swamp forests (average, n=12, standard error of mean)

Study site	Depth	Cold water fraction			Hot water fraction			Hot acid fraction			Non-hydrolysable fraction		
		C [%C_{TOT}]	N [%N_{TOT}]	C/N ratio	C [%C_{TOT}]	N [%N_{TOT}]	C/N ratio	C [%C_{TOT}]	N [%N_{TOT}]	C/N ratio	C [%C_{TOT}]	N [%N_{TOT}]	C/N ratio
P1	0-10 cm	1,16±0,2	1,07±0,3	46,26	12,47±2,1	6,56±1,3	60,64	36,08±5,4	84,45±1,6	12,03	50,29±4,2	7,92±0,7	180,25
	10-30 cm	0,59±0,07	0,66±0,1	29,35	8,08±1,9	5,42±1,5	50,69	48,89±6,7	82,82±2,4	16,45	42,45±5,1	11,10±1,3	112,11
P2	0-10 cm	1,28±0,2	2,87±0,5	22,86	9,03±1,2	12,50±2,0	31,59	48,62±7,2	73,41±5,0	23,43	41,06±6,3	11,22±2,1	118,38
	10-30 cm	0,74±0,08	1,06±0,1	32,43	7,44±0,8	7,67±0,8	31,71	42,34±5,5	78,28±1,9	16,92	49,47±4,5	12,99±0,7	121,61
R1	0-10 cm	0,71±0,07	1,18±0,1	18,50	3,75±2,0	3,07±1,4	27,53	32,00±3,2	79,97±2,3	11,66	63,54±1,7	15,78±1,3	119,46
	10-30 cm	0,45±0,04	0,47±0,07	33,06	2,28±1,8	1,97±1,4	31,53	27,11±1,5	73,04±2,5	12,46	70,17±0,8	24,52±2,7	97,52
R2	0-10 cm	0,74±0,1	0,96±0,2	21,36	2,98±1,5	2,91±1,3	25,06	38,52±2,1	82,41±1,3	13,43	57,77±1,6	13,71±0,4	120,56
	10-30 cm	0,5±0,06	0,45±0,1	37,20	3,45±1,2	2,39±0,7	37,62	35,84±5,7	82,6±2,2	12,06	60,21±6,2	14,57±2,1	121,30
D1	0-10 cm	0,67±0,02	0,77±0,1	22,56	3,86±1,0	2,92±0,9	46,98	28,97±1,4	77,65±1,0	9,28	66,50±1,7	18,66±0,8	121,61
	10-30 cm	0,58±0,06	0,41±0,2	32,27	5,78±2,0	2,94±1,8	42,84	29,28±3,3	77,43±1,6	10,67	64,36±2,8	19,23±1,6	91,54
D2	0-10 cm	0,74±0,09	1,21±0,3	25,71	8,06±0,4	7,09±0,6	51,58	30,91±8,8	68,67±6,7	24,74	60,29±8,9	23,03±6,1	116,08
	10-30 cm	0,50±0,08	0,62±0,1	39,18	6,43±0,5	5,58±1,1	49,71	31,34±7,4	68,87±5,9	17,29	61,73±7,5	24,93±5,7	102,26

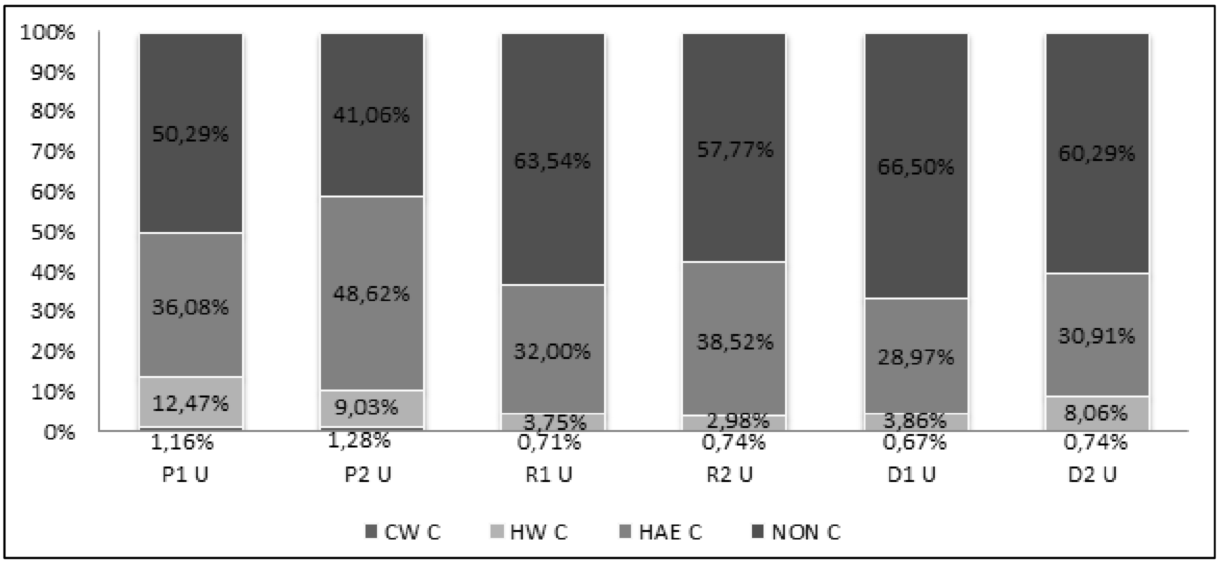

Figure 3 Proportion of C fractions from pristine (P1, P2), restored (R1, R2) and drained (D1, D2) spruce swamp forests in 0-10cm layer. CW C – cold water extractable carbon, HW C – hot water extractable carbon, HAE C – hot acid extractable carbon, NON C – non-hydrolysable carbon.(average, n = 12).

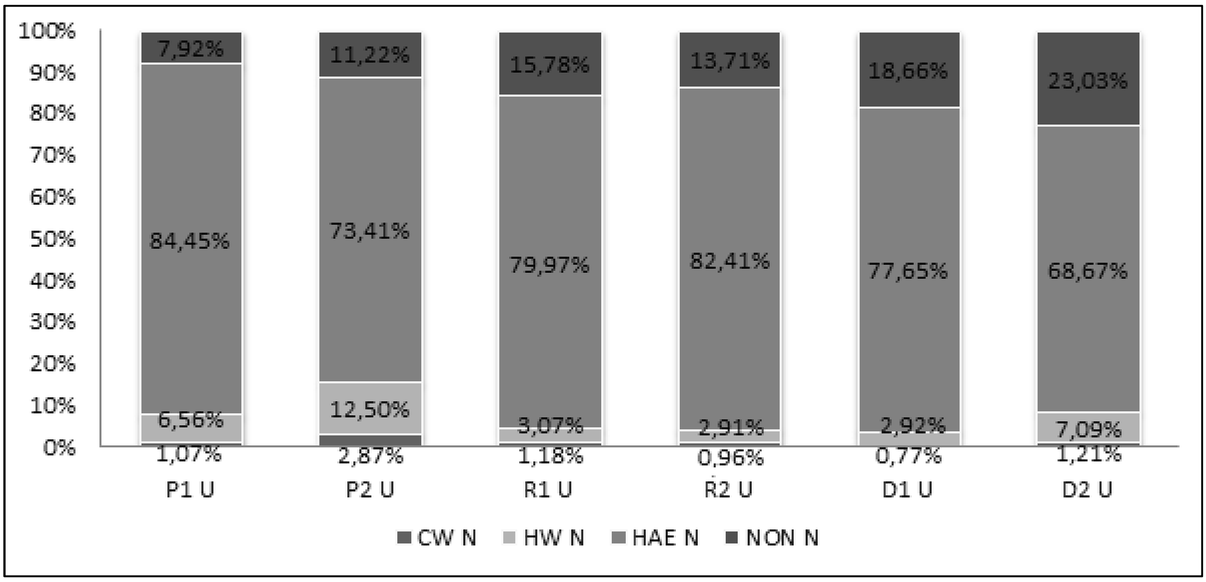

Figure 4 Proportion of N fractions from pristine (P1, P2), restored (R1, R2) and drained (D1, D2) spruce swamp forests in 0-10cm layer. CW N – cold water extractable nitrogen, HW N – hot water extractable nitrogen, HAE N – hot acid extractable nitrogen, NON N – non-hydrolysable nitrogen.(average, n = 12).

SOM of the surface (0-10cm) layer had higher proportion of CW and HW pool than 10-30cm layer (Table 2, Fig. 3 and 4).On average, 0,45–2,87% of total C and total N were released by cold water extraction and 2,2–12% of total C and total N by hot water extraction (Table 2). There were strong differences between the C/N ratios of both HAE and NON pools. The C/N ratio of HAE fraction (10-21) was significantly lower than ratio of the total SOM, because most of the total N was hydrolysed by HAE (68,9-84,45%) in all sites. This also lead to the much higher C/N ratio of NON pool (108,5-146,2) than that of total SOM. Strong differences were in fraction proportions between pristine and both drained and restored sites (Figure 3 and 4, Table 2). CW C, HW C and HAE C pools were the highest on pristine sites whereas NON pool was the lowest, respectively.

Effect of management and soil layers on the SOM fractions

Table 3 Results of RDA analyses

Main effect		Sites	Explained variation	p	pseudo-F
Management	B	All	19,5	0,072	9,6
		R and D	7,5	0,33	4,8
Soil layers	A	All	16,5	0,002	14,6
		R and D	17	0,002	10,4
Interaction between management and soil layers		All	0	0,54	0,9
Distance from ditches		R and D	0	0,59	0,8
Infrared spectroscopy/ management	B	All	28,63	0,002	14,1
Infrared spectroscopy/ soil layer	A	All	3,92	0,048	2,7

*Covariables: A - management, B - soil layers

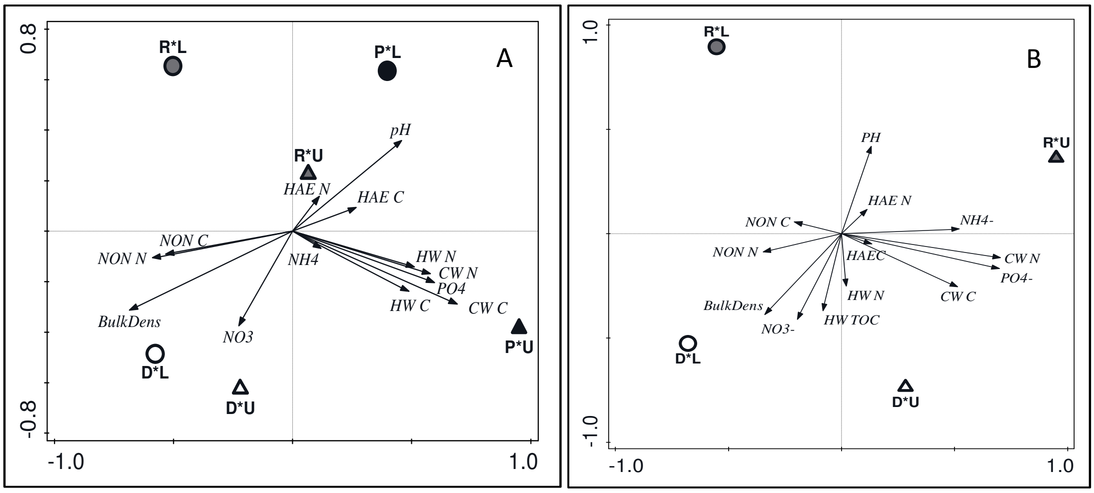

Figure 5 Effect of drainage and restoration and soil layer on soil organic matter quality and on bulk density and pH - RDA analysis (data from fractionation method). **A** – all sites. **B** – drained and restored sites. P*U – pristine sites; 0-10 cm layer, P*L – pristine sites; 10-30 cm layer, R*U – restored sites; 0-10 cm layer, R*L – restored sites; 10-30 cm layer, D*U – drained sites; 0-10 cm layer, D*L – drained sites; 10-30 cm layer.

Results of RDA analyses of management and soil layers effect on SOM quality are shown in table 3. RDA analysis of effect of management and soil layers on SOM quality explained 19,5% and 16,5% of variability of the data, respectively (Table 3). Almost all CW pools (except NO_3^-) and all HW pools tended to the 0-10cm layer of pristine sites (Fig. 5). NON and HW pools, CW C and NO_3^- explained most of the variability. Bulk density and pH as basic characteristics were also one of the most explaining variables. No influence on SOM was observed with increasing distance from ditches in drained and restored sites. And also no interactions between soil layers and management were shown (Table 3).

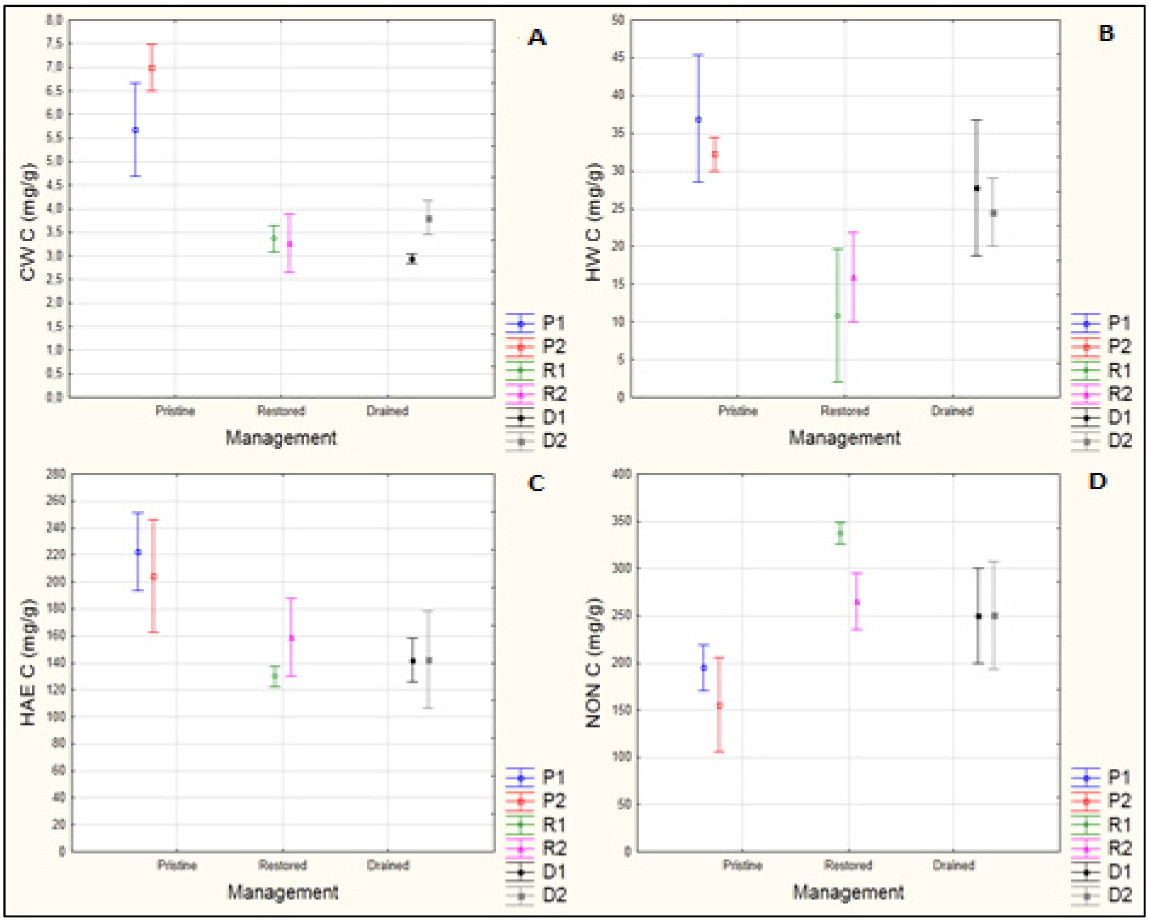

Figure 6 Influence of management **A** on cold water extractable C **B** on hot water extractable C **C** on hot acid extractable C and **6 D** on non-hydrolysable C concentration in soil of pristine, restored and drained spruce swamp forest (average, ± standard error of mean, n = 12).

Soil organic carbon was the most affected variable by drainage and restoration. CW C (figure 6A) (F=14,2; p<0,05) pool was affected by management in 0-10 cm layer, whereas HW C (figure 6B) (F=23,1; p<0,05), HAE C (figure 6C) (F=12,5; p<0,05) NON C (figure 6D) (F=4,9; p<0,05) pools were affected by management in 10-30 cm layer. The effect of management on other soil organic C pools was not significant (p>0,05). The results were different for N pools, where management had negligible effect on all N pools in 0-10 cm layer and for CW N and NON N pools in 10-30 cm layer. However, significant influence of management was observed for HW N ($F=23{,}1$; $p<0{,}05$) and HAE N ($F=12{,}5$; $p<0{,}05$) pools in 10-30 cm layer. NON N and NON C were positively correlated with bulk density and negatively correlated with water table.

Management had no effect on concentrations of NH_4^+ and NO_3^- in cold water extractable pool. NO_3^- concentration was similar at all sites except site D1, where NO_3^- concentration was significantly higher. In lower layer, PO_4^- concentration was affected by management ($F=163{,}6$; $p<0{,}05$) whereas in upper layer the effect of management was not significant. First and second sampling season showed similar results for all NH_4^+, NO_3^- and PO_4^- compounds.

Results of the analysis of soil infrared spectra are in line with the results obtained by SOM fractionation. Management accounted for 28% of the total variation in spectral data, showing a clear effect of site management on SOM quality (Table 3, Fig 7). Compared to the soil of pristine sites, drained soil showed a relative increase of lignin-like (1265 and 1630 cm^{-1}) and aliphatic structures (fats, wax, lipids; 2850 and 2920 cm^{-1}) (Fig. 8, Table 4). Those recalcitrant (decay resistant) structures were still highly abundant in the soil of restored sites.

Soil layer (depth) had a small effect on SOM quality characterized by infrared spectroscopy. Spectral characteristic of the upper and lower layer soil significantly differed, but the effect accounted for only 3% of the total variation in the spectral data (Table 3, Fig. 7).

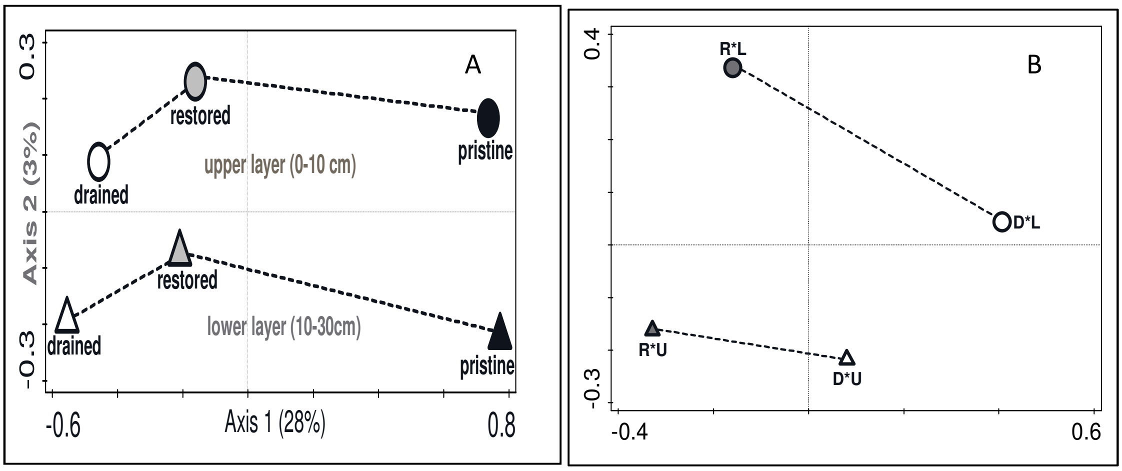

Figure 7 Effect of management and soil layers on SOM - RDA analysis (data from NIRS method). **7A** – all sites. **7B** – drained and restored sites. R*U – restored sites; 0-10 cm layer, R*L – restored sites;10-30 cm layer, D*U – drained sites; 0-10 cm layer, D*L – drained sites; 10-30 cm layer.

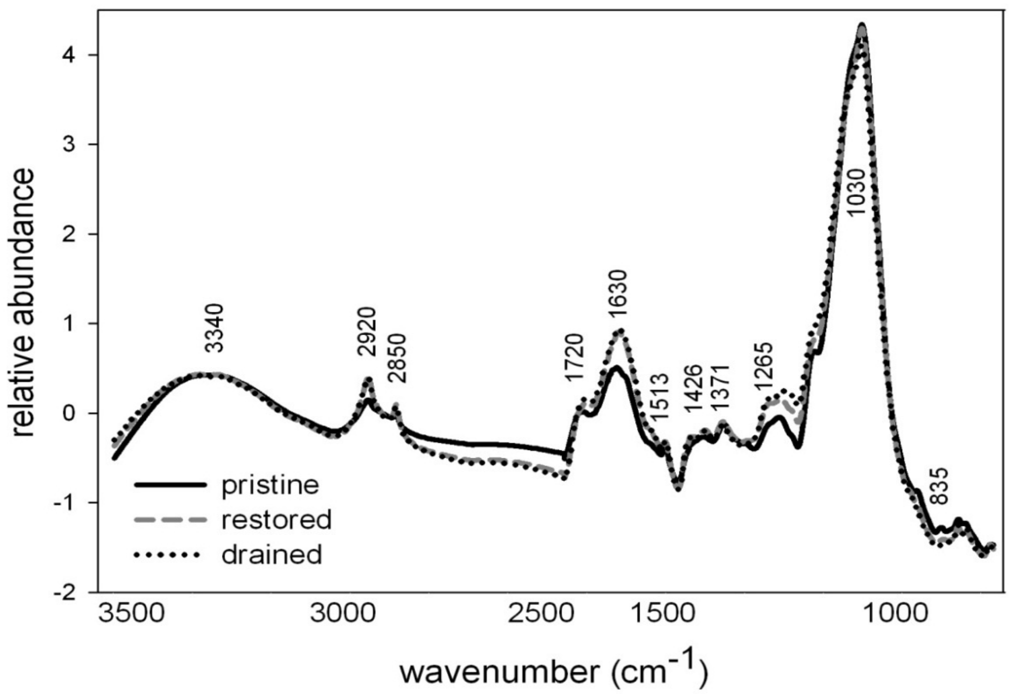

Figure 8 Infrared spectra of peat from pristine, restored and drained spruce swamp forests. Relative abundances for each spectral signal were obtained by standard normal variate transformation and detrending (see Materials and Methods). Characteristic absorption bands of the major biochemical descriptors have been marked on the spectra, see Table 4 for the assignments of the bands.

Table 4. Assignment of the principal descriptive infrared absorption bands in peat samples. Adopted from Artz et al. (2008)

Wavenumber (cm^{-1})	Assignment	Characterization
3340	γ (O–H) stretching	Cellulose, in samples with defined 3340 peak
2920	Antisymmetric CH2	Fats, wax, lipids
2850	Symmetric CH2	Fats, wax, lipids
1720	C=O stretch of COOH or COOR	Carboxylic acids, aromatic esters
1650–1600	Aromatic C=C stretching and/or asymmetric C–O stretch in COO–	Lignin and other aromatics, or aromatic or aliphatic carboxylates
1515–1513	Aromatic CQC stretching	Lignin/phenolic backbone
1426	Symmetric C–O stretch from COO– or stretch and OH deformation (COOH)	Carboxylate/carboxylic structures
1371	C–H deformations	Phenolic (lignin) and aliphatic structures
1265 (approximately)	C–O stretching of phenolic OH and/or arylmethylethers	Indicative of lignin backbone
1080–1030	Combination of C–O stretching and O–H deformation	Polysaccharides
835	Aromatic CH out of plane	Lignin

Discussion

On drained and rewetted sites, NON C was higher than on pristine ones. It was most probably caused by long-term drainage of these sites. In such conditions decomposition was increased by soil aeration and thus left more resistant organic compounds in the soil. The dominance of NON C suggests that the majority of SOM in these sites is relatively recalcitrant (Dolda, 2012). Paul et al., (2006) reviewed, that NON C pool is positively correlated with SOM contents, but our results showed no correlation between NON C and SOM. Paul et al. 2006 postulated that NON pool is not strictly a passive SOM pool. Our results support this statement. Similarly to other studies, C/N ratio of NON pool was very high in our study too (Kogel-Knabner, 1997; Poirier et al., 2003; Uhlířová et al., 2007). Differences between NON C pools support statement of Paul et al. (2001) that the great variability of NON pools could be due to the different organic matter quality and land use among the studied soils. Paul et al. (2006) analysed 1100 data points and the NON pool ranged from 30% to 80% of total SOM. This range is quite consistent with our NON C, which ranged from 41% to 70%. NON pool depends on soil type, depth, texture and management (Paul et al., 2006). Uhlířová et al. (2007) did the same fractionation method in Siberian tussock tundra and theirs proportions of HAE and NON pools differed from our study. Notably NON pool proportion was much higher in our study due to warmer climate and therefore more suitable conditions for decomposition of SOM.

In wetland soils, HAE C pool ranged from 24% to 34% in studies of Paul et al. (2006) and Xu et al. (1997). In our study, HAE C pool ranged from 27% to 49%.The highest HAE C pool (>40%) was found in pristine sites. Higher HAE C in SSF than in other wetland soils can be explained by presence of trees in SSF ecosystem. The different HAE C pools proportion between sites can be caused by higher DOM retention in intact peatlands than in degraded ones (Kalbitz, 2001), due to better sorption and low leaching of DOM. In our study, fraction of carbon pools were shown as the most affected parameter by management, because there were proofed effects of management in all fraction pools either in 0-10 cm or 10-30 cm layer.

Effect of management on CW C was proofed only in 0-10 cm layer; it can be due to the fact that significant part of CW C had been consumed by microbial community before it reached 10-30cm layer. In the study of Curtin (2006), CW pool C/N ratio was wider than C/N ratio of whole SOM, but in our case these ratios were rather similar. It can indicate that recent plant debris with high C/N ratio is a source of the extracted organic matter (Ghani et al., 2003).

HW C was the most affected C pool by management. Significant effect of management on HW C was found in 10-30 cm layer and almost significant effect of management was found in 0-10cm layer (p=0,069). In our study, we found almost significant management effect on HW N in 0-10 cm layer (n=2 F=6,58 p=0,08) and significant effect in 10-30 cm layer (n=2 F=4,91 p=0,014). Surprisingly, the lowest HW C concentration was measured in restored sites, although we assumed that there will be the highest HW C concentration. Ghani (2003) suggests, that loss of HW C in soil system indicates decline of organic labile pools of nutrients such as nitrogen, sulphur and phosphorus, microbial biomass pool and also degradation of soil structure. Although high input of labile organic substrates could occur immediately after restoration (Wilson et al., 2008), these compounds could be leached from the ecosystem, because of water table elevation. HW pool has high correlation with microbial biomass (Haynes & Francis ,1993; Sparling et al., 1998; Ghani et al., 2003; Balaria, 2009) and microaggregation (Haynes & Francis, 1993; Ghani et al., 2003). HW pool is mainly of microbial origin (Haynes & Francis, 1993) and it is bioavailable fraction (Balaria, 2009), therefore it can respond to changes in land use in relatively short-term. This, together with our results, is consistent with statement of Huang (2010) that HW and CW pools can respond rapidly to changes in C supply and that they are sensitive indicators of changes in the SOM caused by different soil management practices (Ghani, 2003). HWEOM has a higher H/C ratio than the whole soil, probably due to the high carbohydrate and low aromatic C content of HWEOM. Similarly to Ghani et al. (2003) HWEOM was a much larger SOM pool than CWEOM. On average, it represented 80% of total water-soluble SOM. Effect of management on all measured variables was almost significant (Table 4). This confirms our results for separately analysed variables in Statistica 10, where differences between pristine sites and other sites were most often. Effect of soil layers was more significant than effect of management. Significant effect of soil layers is consistent with founding’s Huang et al. (2010).

There are some differences in methodology among different authors which could lead to the different results. Ross (2009) used meta-analysis to estimate response of dissolved organic N and CW N concentrations in soils due to the changes in methodology of extraction by hot water. They found that drying soil samples at 20 °C prior to extraction increase water extractable N by 245%. The increase was correlated to the drying temperature. We used freeze-drying in our experiment to eliminate this influence. Another difficulty occurs in HW methodology. Hot water (80°C) is sufficient to release microbial components and hydrolysed more stabilized polysaccharides low in uronic acids (Haynes & Swift, 1990).As stated above, HW pool have high correlation with microbial biomass. Rees & Parker (2005) found, that filtration through 0.45 µm Millipore filters can increase correlation with soil microbial production of CO2 and dehydrogenase activity. Without filtration, they extracted even more CW C, but no correlation with biological activity was observed. However, filtration of DOM can cause artefacts through adsorption, desorption, and cavitation (Zsolnay, 2003).

Holl et al. (2009) showed that the short-term and long-term effects of rewetting on DOM are different. Kalbitz et al. (2002) and Zakk et al. (2006) found elevated DOM concentrations in short-term restored peatlands. High DOM concentration occurs especially during dry periods in summer, when water table is not close to the surface. Holl et al. (2009) studied long-term effects of rewetting on DOM and they found reduced DOM concentrations following rewetting. In the soil depths of 40 and 60 cm different redox conditions in restored and moderately drained fens were found, although water saturation was similar. This suggests that long-term stable water table (close to the surface) is necessary to create strongly reducing redox conditions. Under such redox conditions low DOM concentrations are then found. Our results support these findings. In our study, DOM quality was not significantly different between restored and drained sites, although basic environmental characteristics like pH, bulk density or plant coverage differed between sites. This suggests that longer time than 7 years of restoration is necessary to change DOM quality of previously drained SSF.

5 Conclusions

The study demonstrates how soil organic matter quality responded to drainage and water regime restoration of spruce swamp forest ecosystems.

Soil organic matter (SOM) quality differed between pristine and drained and between pristine and restored sites. All C pools were affected by drainage. Hot water extractable C pool was the best indicator of effect of drainage on SOM quality. This pool together with cold water extractable C includes total microbial biomass and also most of the C easily available for microbial decomposition. Therefore long-term drainage will lead to decrease of C available for microbial community, decrease of heterotrophic microbial activities and slow down of organic matter decomposition in soil. On the other hand, N pools were not as good indicators of SOM quality change as C pools.

Restoration of spruce swamp forest (3 to 7 years period) did not have any significant effect on SOM quality as compared to drained systems, although other parameters, like bulk density, water table and plant community composition differed between the restored and drained sites.

Infrared spectroscopy method was also used to test SOM quality and the results showed the same trends as chemical fractionation method.

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Figures

Figure 9 Restored site R1.

Figure 10 Pristine site P1.