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Response of peat biogeochemistry and soil organic matter quality to rewetting in bogs and spruce swamp forests

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ABSTRACT

Various peatland restoration strategies developed during the last two decades have aimed to stop degradation and bring back the original hydrology, biodiversity and other peatland functions. This study evaluated progress 6–15 years after rewetting in vegetation development, physicochemical properties of peat, soil organic matter (SOM) quality and microbial activity in previously long-term drained bogs and spruce swamp forests (SSF) in comparison with pristine and long-term drained sites in the Bohemian Forest, Czech Republic.

Long-term drainage led to overall ecosystem degradation, indicated by a change in vegetation composition, reduced decomposability of peat, with high content of recalcitrant compounds and decreased pH, and reduced soil microbial biomass and activity. The degradation was more pronounced in SSF, while bogs seemed to be relatively resistant to environmental changes caused by drainage. Post-rewetting progress has occurred with regard to vegetation composition, peat pH, microbial biomass and potential anaerobic CO_2 and CH_4 production, all of which tending towards characteristics of the pristine sites. However, overall SOM quality has not yet responded significantly, indicating that some peat properties and functions, such as C accumulation, need much longer periods of time to return to the original level.

1. Introduction

Peatlands accumulate organic matter under the prevailing waterlogged conditions, which constrain litter decomposition [1]. The position of the water table controls the balance between peat accumulation and decomposition. Therefore, peatland functioning is very sensitive to changes in hydrology that may be caused by climate or land use changes [1]. There is a strong argument for the protection and restoration of peatlands for the sake of the hydrological, biological and carbon (C) sequestration ecosystem services they offer [2,3]. In Central Europe, peatlands – as a relict boreal ecosystem – significantly contribute to biodiversity and play an important role in the hydrology of the landscape. However, most peatlands in this region were destroyed or have been disturbed by human activities [4,5]. The Bohemian Forest, including the Šumava National Park, is an exceptional area within Central Europe due to the abundance of peatlands; however, about 70% of them have been influenced by drainage. Large-scale restoration efforts were initiated more than a decade ago, with the aim of revitalising the bogs and spruce swamp forests (SSF) characteristic for this region.

Artificial drainage and peat mining disturb the natural processes of peat formation and accelerate soil organic matter (SOM) mineralisation, resulting in a net release of C [6]. Drainage generally results in changes in vegetation composition accompanied by changed litter quality, which are followed by changes in peat physicochemical properties and nutrient availability [5,7,8]. Long-term exposure of the surface peat layers to aerobic decomposition in drained or cutaway peatlands results in decreased quality and decomposability of SOM. Labile SOM fractions are depleted and recalcitrant fractions predominate [9]. Low availability of substrate and unfavourable C:N:P stoichiometry of peat and incoming litter is reflected in decreased microbial biomass and activity [7,10–12]. The extent of changes in ecosystem functioning (degradation) depends on the intensity of the disturbance. It also varies between different peatland types, with more pronounced draining effects in nutrient-richer minerotrophic fens than nutrient-poor and acidic ombrotrophic bogs [10,13,14]. Based on existing data from drained and restored peatlands, a more dynamic response to hydrological restoration can be expected in fens than in bogs, especially dieback of trees, changes in light conditions and relatively fast proliferation of the plant species characteristic of undrained sites [15–17].

A number of peatland restoration activities have been developed

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during the last two decades with the aim to stop degradation and bring back the original ecosystem functions such as peat formation, water retention and biodiversity [2,18]. Typical peatland vegetation can be quickly restored and is therefore the most visually obvious indicator of restoration progress, while recovery of other (belowground) ecosystem attributes may take longer [19,20]. Microorganisms are the main drivers of SOM transformations and therefore their activity and abundance may reflect SOM quality and physicochemical properties [8,10,21]. Studies with cutaway peatlands determined that poor substrate quality was the main reason for low microbial biomass and low CO_2 and CH_4 production during the first years after rewetting [22–24]. It is thus assumed that the spreading of peatland vegetation and accumulation of new litter following this intervention will lead to an improvement of SOM quality in the surface layer. This can be assessed by Fourier Transform Infrared (FTIR) spectra analysis of peat, which has been found a useful tool for evaluation of SOM composition and monitoring of restoration efforts [25]. Vegetation succession after rewetting can result in differences in SOM in terms of C availability, which can be reflected in increases of microbial biomass and activity [26]. For example, methanogenic archaea and CH_4 dynamics are known to react sensitively to environmental changes [10,27]. Therefore, the regeneration of CH_4 production after peatland rewetting might be considered not only as an indicator of stable anaerobic conditions but also of the re-establishment of original microbial processes and substrate availability [23]. Nurulita et al. [28] suggest that soil pH, enzyme activities and soil microbial diversity may be useful indicators in terms of monitoring restoration progress.

This study aimed to evaluate the succession of vegetation after the rewetting on previously long-term drained bogs and SSF and to investigate whether the vegetation shift is reflected belowground in peat physicochemical properties and shifts in microbial activities, including enzyme activity. Specifically, we (i) compared the responses of SSF and bogs to long-term drainage and rewetting with a focus on vegetation and peat biogeochemical properties, SOM quality and production of CO_2 and CH_4 and (ii) assessed the restoration progress in a SSF four years after a previous study by Mastný et al. [29], who evaluated SOM quality and microbial activity 3–7 years after rewetting of the same SSF study sites. (iii) Based on our results, we put forward ecologically meaningful indicators in order to improve future monitoring of restoration schemes.

We hypothesised that peat at long-term drained sites has a higher C:N:P stoichiometric ratio and a high proportion of recalcitrant SOM, resulting in low soil microbial activity. Rewetting connected with recolonisation by characteristic peatland vegetation will reverse this trend and peat properties will start to change back towards the original state. We expected that microbial activities driven by the input of recent plant assimilates would respond more rapidly than overall peat quality and enzyme activity linked to peat decomposition. Lastly, we expected that bogs would be more resistant and SSF more sensitive to shifts in hydrological conditions.

2. Material and methods

2.1. Study sites

We selected 12 sites in the Bohemian Forest, south-western Czech Republic (48°59′ N, 13°28′ E), representing two main types of peatlands: bogs (BOG) and spruce swamp forests (SSF). The study sites ranged in altitude from 1100 to 1260 m a.s.l.; mean annual precipitation was between 1000 and 1200 mm and mean annual temperature between 3.2 and 4 °C (1961–1990, statistics by the Czech Hydro-Meteorological Institute).

For each peatland type, six study sites were selected, two each of three different management types: i) pristine (unmanaged) peatlands (BOGp n = 2, SSFp n = 2); ii) long-term drained peatlands (BOGd n = 2, SSFd n = 2); iii) rewetted (restored) peatlands after long-term drainage (BOGr n = 2, SSFr n = 2). The rewetting of the two BOGr sites was done 6 and 15 years and that of the two SSFr sites 6 and 9 years before this study, respectively. All the disturbed sites were drained in the 1960s to increase forest productivity; however, no tree planting or other type of management was carried out after drainage and the sites were left abandoned. Rewetting was achieved by blocking ditches, using timber dams and partial filling of ditches with organic material.

BOGp were dominated by common plant species characteristic for different microhabitats (hummocks, hollows and lawns) such as *Andromeda polifolia*, *Vaccinium uliginosum*, *Eriophorum vaginatum*, *Carex limosa* and *Trichophorum caespitosum. Sphagnum rubellum*, *S. capillifolium* and *S. magellanicum* dominated the moss layer. BOGd and BOGr mostly lacked the microtopographical variation of BOGp, especially the hollows, and were dominated by *V. uliginosum*, while young trees of *Picea abies* or *Pinus* x *pseudopumilio* proliferated on the driest places. The dwarf shrubs and trees partly died off along the dammed ditches in the BOGr sites, with original species such as *E. vaginatum* and *Sphagnum* mosses spreading.

SSFp were also characterised by wetter and drier microhabitats occupied by heterogeneous vegetation, such as *E. vaginatum* together with other sedges and grasses or *Vaccinium* dwarf shrubs. The moss layer was dominated by *S. fallax*, *S. flexuosum* and *S. girgensohnii*. The tree canopy consisted of *P. abies* with a height of about 8–15 m, covering 0–70%. SSFd were characterised by the wholly dominant *V. myrtillus*, a dense tree canopy (*P. abies*; 100% cover) with a height of about 20 m and a fragmented moss layer with greater cover of forest mosses (*Pleurozium schreberi, Dicranum* spp., *Polytrichum commune, Hylocomnium splendens*). On SSFr, *E. vaginatum* and *Sphagnum* mosses were spreading.

2.2. Peat sampling and basic analyses

The sampling procedure used a systematic design of six sampling plots within a 20 × 20 m^2 area at each site. The sampling plots were placed in two parallel, 20 m long transects perpendicular to the ditch. On each transect, peat was sampled at a distance of 1, 10 and 20 m from the drainage ditch. The vegetation was characterised near each sampling plot as % cover for each plant species in a 1 m^2 area. The hollows and tops of hummocks in bogs were not sampled. The water table was measured manually every other week during the growing season in perforated PVC tubes, whose spacing reflected the soil sampling design on each site.

Peat was sampled using a box corer (6.5 × 5.5 cm^2 inner dimension) to a depth of 30 cm and the cores were divided into upper (0–10 cm) and lower (10–30 cm) layers. The peat samples were homogenised by hand and woody material and roots were removed.

A portion of each sample was dried at 60 °C to constant weight, milled and analysed for total C (C_{TOT}) and N (N_{TOT}) content with a Micro-cube elemental analyser (Elementar, Germany). Total P (P_{TOT}) was measured colorimetrically as orthophosphate on a flow injection analyser (FIA, Lachat QC8500, Lachat Instruments, USA) after perchloric acid digestion. Soil pH was measured after shaking 10 g of fresh sample with 25 mL of distilled water and letting it stand for 2 h. Bulk density was determined by weighing the individual intact samples after drying at 70 °C.

2.3. Microbial biomass and CO_2 and CH_4 production

Soil microbial biomass C (C_{mic}) and N (N_{mic}) were measured after chloroform fumigation-extraction of fresh peat samples [30]; concentrations of dissolved organic C and dissolved N in the soil solution were analysed with a LiquiTOC II (Elementar, Germany). C_{mic} and N_{mic} were calculated as the differences between C and N contents in fumigated and non-fumigated samples, using correction factors of 0.3 [30] and 0.54 [31], respectively.

Microbial activity was characterised as potential aerobic and