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RESTORATION OF RAISED BOGS: BIOGEOCHEMICAL PROCESSES INVOLVED IN THE RE-ESTABLISHMENT OF SPHAGNUM-DOMINATED VEGETATION

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Abstract: Restoration of bog remnants by hydrological measures generally leads to inundation and rapid development of *Sphagnum* vegetation when poorly humified peat is still present. The peat either swells up or becomes buoyant, creating a favourable substratum for *Sphagnum*. In many cases, however, only strongly humified peat is remaining and *Sphagnum* redevelopment is usually not observed. Waterlogging of peat remnants is therefore preferred in this case. Bulk density, peat structure and methane production all play an important role in the buoyancy of floating peat and newly formed *Sphagnum* carpets. Methane appears to provide peat buoyancy. Peat characteristics such as C/P and lignin/P ratios, and pH, determine decomposition rates and hence methane and carbon dioxide production. On locations where only strongly humified peat is present, floating raft formation can be stimulated by the introduction of peat with suitable characteristics. Methane production rates in acidic substrates can be enhanced by mixing the peat with small amounts of lime. Substrate derived carbon dioxide and methane both appear to serve as an important carbon source for *Sphagnum*. High carbon dioxide concentrations in the acrotelm strongly stimulate hummock formation by *Sphagnum magellanicum*. Typical hummock species are, however, usually very slow colonisers. Introduction of these species in carpets dominated by *Sphagnum cuspidatum* or *Sphagnum fallax*, or on bare peat, appears to be very promising. The results show that biogeochemical and ecophysiological knowledge is vital for the choice of sound bog restoration strategies.

Keywords: *Sphagnum* acid bogs, *Sphagnum* species, desiccation, identifying appropriate conservation and restoration objectives

Introduction

The present-day scarcity of typical bog vegetation has made the restoration of cut-over bogs an important issue. The aim of restoration management is to restore cut-over bogs into regenerating, self-sustaining ecosystems with the appearance and composition of 'natural' bogs (Wheeler & Shaw, 1995). In restoring the hydrologically self-regulating capacity of degraded bog remnants, the re-development of a functional acrotelm appears to be essential (Joosten, 1995; Wheeler & Shaw, 1995). As *Sphagnum* mosses can only grow under wet conditions, rewetting of drained peat bogs is normally the first step in peat bog restoration. However, rewetting does not always result in the desired redevelopment of *Sphagnum* mats. In this short paper we discuss and explain various peat bog restoration strategies relating to peat quality, water chemistry and hydrology based on studies from the Netherlands.

Materials and methods

In this paper we present the results of field observations, field experiments and lab experiments. A detailed description of the materials and methods used can be obtained from Smolders et al. (2003) and Tomassen et al. (2003; 2004).

Results and discussion

Peat quality

The quality of the residual peat seems to be a crucial factor determining the success rate of cut-over bog restoration. When still poorly humified peat is present, hydrological measures generally lead to inundation and rapid development of *Sphagnum* vegetation. The peat either swells up or becomes buoyant, both creating a favourable substratum for *Sphagnum*. In many cases, however, only strongly humified peat is remaining and *Sphagnum* redevelopment is usually not observed. As the degree of peat decomposition determines the residual decomposition rate, it thereby influences carbon availability. Carbon produced by these anaerobic decomposition processes (carbon dioxide and methane) proves to be an important carbon source for *Sphagnum* mosses.

Growth of submerged Sphagnum

Under optimal growing conditions, submerged *Sphagnum cuspidatum* is able to fill up the entire water layer, forming a loose raft on which other species may ultimately establish. Peat-derived carbon dioxide (CO₂) is an important carbon source for submerged growing *Sphagnum cuspidatum* (Paffen & Roelofs, 1991; Smolders et al., 2003), and very probably also for emergent *Sphagnum* species (Smolders et al., 2001). In addition to CO₂, submerged *S. cuspidatum* requires sufficient light. Humic acids from the remaining peat substrate, however, colour the water layer and light limitation can very easily hamper the growth of submerged *Sphagnum*. This explains why in peatlands submerged *Sphagnum* is normally absent from waters whose depth exceeds 0.5 m (Lamers et al., 1999; Smolders et al., 2003). The availability of both light (clear water and/or very shallow water) and CO₂ have to be sufficient to enable submerged *Sphagnum* to reach high photosynthetic and growth rates. These conditions are frequently not met in inundated peatlands.

Table 1. Some physical and chemical prerequisites for peat able to form floating rafts after deep inundation of cut-over bogs. Data are based on the analysis of buoyant peat collected from 6 locations in the Netherlands (n = 13) (after Tomassen et al., 2004).

Chemical characteristics	Buoyant peat
pH	≥ 4.0
Bulk density (g DW l ⁻¹ FW)	≤ 75
Fraction < 1 mm	≤ 0.50
Fraction > 5 mm	≥ 0.40
P (μmol g ⁻¹ DW)	≥ 10
C:P ratio (g g ⁻¹)	≤ 3000
CH ₄ production rate (μmol g ⁻¹ DW d ⁻¹)	≥ 2
Lignin (mg g ⁻¹ DW)	≤ 300
Lignin:P ratio (g g ⁻¹)	≤ 1000
pH:(bulk density) ratio	≥ 0.05

Buoyancy of residual peat

The buoyancy of floating peat mats is caused by CH₄ bubbles accumulating in the peat (Scott et al., 1999; Lamers et al., 1999; Smolders et al., 2002), so methane production rates play an important role in the buoyancy of residual peat after inundation. This

floating peat provides favourable conditions for peat mosses and for peat accumulation, as they provide permanently wet conditions but are never flooded (Money, 1995; Joosten, 1995; Lamers et al., 1999). The highest CH₄ production rates are measured in poorly humified peat. Table 1 summarizes some of the physical and chemical characteristics of peat that predispose the peat to becoming buoyant after inundation. The ratio of pore water pH (squeezed from the peat) to peat bulk density appears to be a simple and reliable indicator of whether the peat is suitable for the formation of floating peat. Among the other appropriate peat characteristics for determining buoyancy are the C:P and lignin:P ratio, and the size of the peat particles (Table 1).

In most cut-over bogs, however, the residual peat is inadequate for floating raft formation, since it is mostly the strongly humified catotelm peat which is left. The introduction of poorly humified organic substrates from donor sites might be useful to stimulate floating rafts. A feasibility study (Tomassen et al., 2003) has been carried out successfully. Poorly humified substrates derived from sod-cutting in wet heathlands and from peat cutting activities in bogs all appeared to become buoyant if pore water pH was higher than 4.5. If the substrate was too acidic, incorporation of small amounts of lime was necessary to raise its pH and to stimulate CH₄ production and so buoyancy of the substrate (Figure 1; Smolders et al., 2003; Tomassen et al., 2003). The amount of lime that has to be added to obtain these values will depend on the acidity of the substrate, but in the substrates used in the experiment this did not exceed 2 g kg⁻¹ FW.

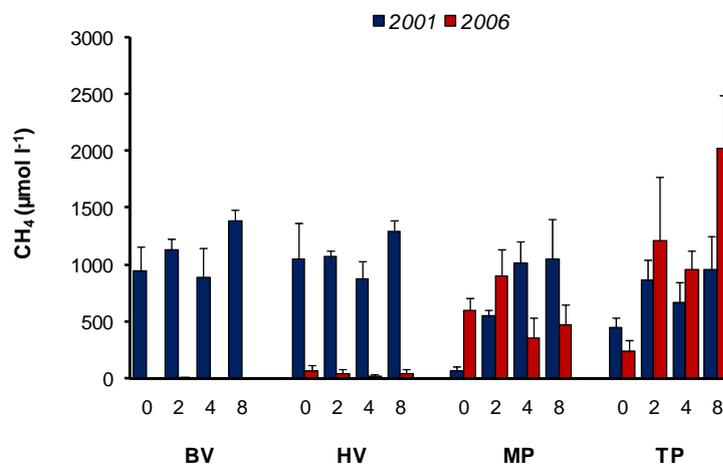


Figure 1. Peat water methane concentration (means + 1 SE; n = 4) measured in peat from four locations and mixed with various amounts of lime (0, 2, 4 and 8 g lime kg⁻¹ fresh peat) in October 2001 (6 months after the experiment started) and in December 2006 (after 5,5 years). For more detailed information about the experimental setup see Tomassen et al. (2003). Statistic results for 2006: effect peat type = $P \leq 0.001$, lime = $P \leq 0.05$ and the interaction between peat type and lime (peat * lime) = $P \leq 0.01$. Peat types: BV = Bargerveen, HV = Haaksbergerveen, MP = Mariapeel, TP = Tuspeel.

Once the bare substrates become buoyant it will be necessary that they are colonized by *Sphagnum* mosses. Re-vegetation of the substrates is important because anaerobic decomposition of fresh and thus easily decomposable organic material has to provide sufficient CH₄ to warrant buoyancy on the long term. The long term feasibility study shows the importance of the accumulation of fresh peat. As a result of high methane production rates (HV substrates) and the absence of peat accumulation, methane concentrations dropped within 5 years (Figure 1) and buoyancy of the substrates was lost.

Introduction of Sphagnum

If floating rafts develop, they frequently remain dominated by *Sphagnum cuspidatum* or *Sphagnum fallax*. Although the development of a vegetation dominated by these species should be regarded as positive, if only because they may provide a good substrate for the target species *Sphagnum magellanicum*, *S. papillosum* and *S. rubellum* (Wheeler & Shaw, 1995), it is essential that vegetation types dominated by the target species develop. These species are more productive and resistant to decay and are therefore able to produce the right acrotelm characteristics. The poor colonization rate by the target species seems to be the main reason why these species remain absent after restoration. Introduction of these target species will enable or facilitate the formation of an acrotelm layer with self-regulating hydrological conditions, which is a prerequisite for a functioning, carbon-fixing bog system.

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