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RESEARCH ARTICLE

Restoration of a Terrestrialized Soak Lake of an Irish Raised Bog: Results of Field Experiments

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Abstract

Soaks (areas of mesotrophic/minerotrophic vegetation within acid bog) add to the overall heterogeneity and biodiversity of raised bog landscapes due to the presence of flora and fauna communities not typically associated with acid bog systems. A field experiment was set up to investigate the potential to restore the minerotrophic and aquatic communities that previously occurred within a soak of an oceanic raised bog in Ireland, which has recently undergone acidification with the expansion of acid bog type vegetation. Three different treatments, control (intact sphagnaceous raft), permeable (sphagnaceous raft removed), and enclosed (sphagnaceous raft removed and plots isolated from surrounding surface water influence) were applied to a total of six plots (each measuring 4 × 4 m), each treatment consisting of two replicates. Within 3 years a sphagnaceous raft with similar vegetation to the surroundings had developed in both permeable plots, while aquatic communities similar to those that occurred at the site in the past had established within the enclosed pots. Our results show that with manipulation of local hydrology it is possible to recreate conditions suitable for aquatic plant communities that once characterized the site. The results also give an insight into the likely processes responsible for the initial terrestrialization of the entire soak over the past century. Application of the results in relation to the site and the widespread practice of restoring bog vegetation on degraded peatlands are discussed.

Key words: acidification, fen, floating raft, methane, minerotrophic, wetland restoration.

Introduction

In Europe peatland conservation and restoration is now a major topic due in part to the extensive loss of the peatland resource as a consequence of exploitation for fuel and conversion to agricultural land (Wheeler et al. 1995; Schouten 2002). Oceanic raised bogs are a distinct type of peat bog that once occurred throughout north-western Europe (Moore & Bellamy 1974). However, only a tiny fraction of sites remain and of those that do, the finest examples occur in Ireland (Goodwillie 1980; Cross 1990; Douglas et al. 2008).

"Soak" is a term used to describe an area of fen vegetation occurring within an acid bog, which is often associated with internal drainage features (Gore 1983). The presence of fen vegetation is due to increased nutrient/mineral supply by either minerotrophic water or the lateral throughflow of ombrotrophic water from the surrounding bog expanse (rheotrophic) (Osvald 1949; Connolly et al. 2002). In contrast to the nonwooded vegetation dominated by ericaceous shrubs and *Sphagnum* mosses that typifies the oceanic raised bogs, soaks are characterized by oligo-mesotrophic open-water communities (with floating macrophytes such as *Nuphar lutea* and *Potamogeton natans*), poor fen (with species such as *Carex rostrasta*, *Potentilla palustris*, *Hydrocotyle vulgaris*, *Sphagnum fallax*, and *Sphagnum squarrosum*), and/or bog woodland vegetation (usually dominated by *Betula pubescens*) (Cross 1990). Soaks support a relatively high diversity of species and unusual flora and fauna assemblages not typically found within oceanic raised bogs (Overbeck 1975; Reynolds 1990; Crushell 2008), thereby adding to the heterogeneity and biodiversity of the ecosystem type.

Soaks were once widespread on Ireland's larger raised bogs but are now extremely rare as a consequence of large-scale exploitation of peatlands (Osvald 1949; Ryan & Cross 1984). Those soaks that do remain have been degraded and continue to be threatened mainly by the effects of drainage around bog margins (Cross 1990; Connolly et al. 2002).

This study focused on a soak known as Lough Roe located within Clara Bog in central Ireland. The soak is of the minerotrophic type as described by Connolly et al. (2002), showing a mineral groundwater influence.

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Palaeoecological studies indicate that it had been an open water body for over 6,000 years (Connolly et al. 2002) and recent research confirms that minerotrophic conditions prevailed at the site throughout this period (total Ca:Mg of peat >10 mol/mol) (Crushell et al. 2009). This research has found that the increased mineral content within the soak is most likely to have originated from the calcareous clay layer underlying the bog. Minerals from the upper part of this layer are thought to have been leached and transferred toward the soak via a local hydrological flow during the early development of the bog. The mineral rich conditions were maintained and continued to exist at the site until recent time due in part to the continued recycling of minerals as a result of high decomposition rates (Crushell et al. 2009). The soak lake was at its maximum extent (circa 1.2 ha) during the nineteenth century, prior to terrestrialization commencing in the early twentieth century (Crushell et al. 2008). Terrestrialization continued throughout the twentieth century and by 1978 an area of approximately 125 m^2 of open water remained, surrounded by a floating minerotrophic raft (*scragh* or *schwingmoor*) containing a high abundance of minerotrophic species (Crushell 2008). This type of minerotrophic community is rare in Ireland and even more notable was its presence near the center of an acid raised bog with no obvious source of mineral rich water nearby. The formation of floating rafts plays an important role in the terrestrialization of open waters in peat bogs. Hereby, peat becoming buoyant due to the production of methane gas and the subsequent accumulation of methane bubbles is a crucial process (Lamers et al. 1999; Smolders et al. 2002). On the other hand, methane production is dependent on the availability of degradable organic acids (dissolved organic carbon [DOC]), temperature, and pH (Dunfield et al. 1993; Tomassen et al. 2004).

It has been shown that major changes occurred in the vegetation communities of the soak during the period 1978–2003, with increased cover of ombrotrophic communities and a decline in the more valued minerotrophic vegetation accompanied by increased acidity of surface water (Crushell 2008).

In this paper, we report the results of a field experiment that was set up to investigate the effectiveness of restoration measures aimed at replicating conditions that were present within the soak prior to terrestrialization (i.e., recreation of open water, a reduced influence of surrounding acid bog water, and an increase of minerotrophic conditions at the soak surface). These measures included removal of the floating sphagnaceous raft thus recreating open water and isolation of the newly formed open water areas from the surroundings to eliminate the influence of acid surface water. Species nomenclature follows Stace (1997) for higher plants and Blockeel & Long (1998) for bryophytes in this paper.

Following the application of treatments, water chemistry and vegetation were monitored within each plot. Two years after the application of measures, major differences were noted in floating peat formation (and vegetation development) between treatments. To determine whether decomposition processes could explain these differences, temperature and methane production in the peat substrate and DOC concentration of pore water were measured from each treatment.

We hypothesize that by removing the influence of the surrounding acid surface water there would be a better prospect for open water conditions with a minerotrophic influence to remain for a prolonged period.

Methods

Study Site

Clara Bog (lat 53°19′N, long 7°36′W) is the largest remaining relatively intact raised bog in Ireland and has long been recognized as being of high ecological importance due in part to the presence of unusual soak systems (Ryan & Cross 1984; Schouten 2002). Lough Roe soak is a terrestrialized minerotrophic lake located on the eastern side of the bog (Fig. 1). The former lake surface consists of a floating raft dominated by species indicative of poor fen conditions with *Sphagnum fallax* and *Sphagnum squarrosum* dominating the moss layer and species such as *Menyanthes trifoliata* and *Carex rostrata* most abundant in the herb layer. This vegetation type has expanded in recent years replacing the more diverse minerotrophic communities that occurred in the past. See Connolly et al. (2002) for further site details.

Experiment Design and Layout

A total of six sampling plots within Lough Roe were selected. The plots are located in the central area of Lough Roe, which is historically the core minerotrophic area that was last to undergo terrestrialization and where the lake sediment (highly decomposed peat) is in contact with the underlying fen peat (Connolly 2002). Each plot measured 4 m × 4 m.

Three different treatments, control, permeable, and enclosed, were applied to the plots. Each treatment comprised two duplicates (only two replicates were possible due in part to the scale of the feature and the difficulty in removing the raft without causing major disturbance to surrounding habitat) randomly distributed over the six plots (Fig. 2). Two plots (control) were left intact. From the other four plots (permeable and enclosed), the floating scragh was removed thereby recreating open water conditions. The depth of water was circa 1 m. The substrate at the bottom of the excavated plots was a highly decomposed liquid peat. The scragh was removed manually using a Rutter Spade and a Grab Fork. The extracted material was discarded in nearby drains outside of the soak, eliminating the possibility that the organic material would contribute to eutrophication of the soak.

In the permeable plots, porous plastic membranes were installed surrounding the open water to a depth of 1.2 m. This membrane prevented vegetation from encroaching into the plot but facilitated the flow of surface water between the plot and the area outside. In the enclosed (impermeable) plots, impermeable membranes (rubber butyl) were installed

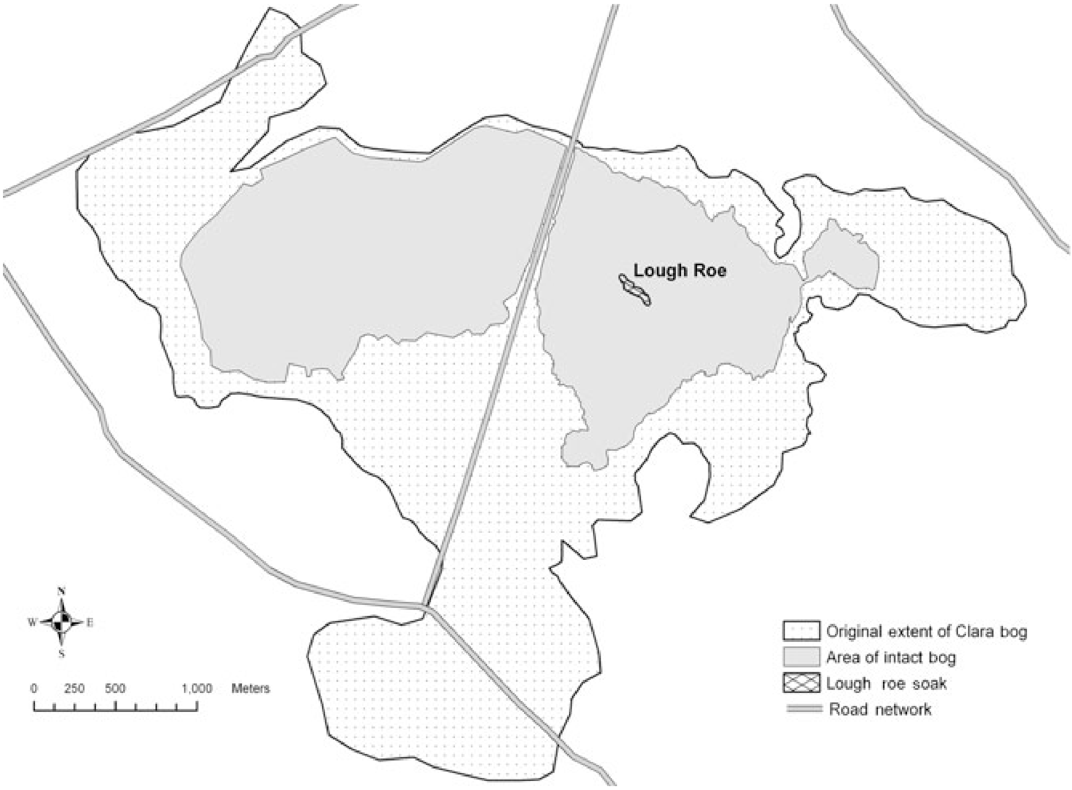

Figure 1. Map showing the location of Lough Roe soak within Clara Bog, County Offaly, Ireland.

surrounding the open water to a depth of 1.2 m. This membrane isolated the plot from surrounding surface water and vegetation.

Soil moisture samplers (Rhizon SMS—5 cm; Eijkelkamp Agrisearch Equipment, The Netherlands) were installed within each plot at three depths (5–10 cm, 0.5 m, and 1 m) to collect pore water samples.

Hydrochemistry Sampling and Analysis

Water samples were taken at monthly intervals (November 2003–November 2004) from three depths (surface, 0.5 and 1 m) within each plot. A total of 234 water samples were taken over the 13-month period. Samples were collected in 60-mL syringes. The pH of water samples was determined immediately using a standard $Ag/AgCl_2$ electrode connected to a pH meter (radiometer Copenhagen type PHM 82). Alkalinity was determined within 24 hours by titrating 25 mL of sample water with 0.01 M HCl to pH 4.2 (Smolders et al. 2002). Next, total inorganic carbon concentrations were measured using an infrared carbon analyzer (model PIR-2000, Horiba Instruments, Irvine, U.S.A.). Samples were then stored in iodated polyethylene bottles (50 mL) at -20°C and later analyzed for total concentrations of other elements using an inductively coupled plasma optical emission spectrophotometer (ICP-OES, Spectroflame, IRIS Intrepid II, Thermo Electron Corporation, Franklin, MA, U.S.A.). Pore water methane concentration was determined as described by Smolders et al. (2002). DOC of pore water was measured from samples taken during June 2006. Samples were filtered through Whatman GF/F filters (0.7 m), stored frozen, and analyzed using a combined ultraviolet wet oxidation technique.

Vegetation Development

After excavation (October 2003), the four excavated plots comprised open-water habitats and were devoid of vegetation. The vegetation of each of the six plots was recorded annually during July for 3 years following excavation. On each sampling occasion all vascular plants and bryophytes were recorded, and their percentage cover visually estimated and recorded in a cover abundance scale as presented in Table 1.

Methane Production

Potential methane (CH_4) production rates of the substrate (a highly decomposed peat taken from a depth of circa 1 m) of each plot were measured by incubating 50 g of fresh peat anaerobically in 250-mL infusion flasks sealed with airtight stoppers (Smolders et al. 2002). Samples were collected on two occasions (October 2004 and August 2005), and incubations were carried out in triplicate for all six plots. After the flasks had been filled, the gasses were evacuated and then flushed three times with pure nitrogen gas to remove

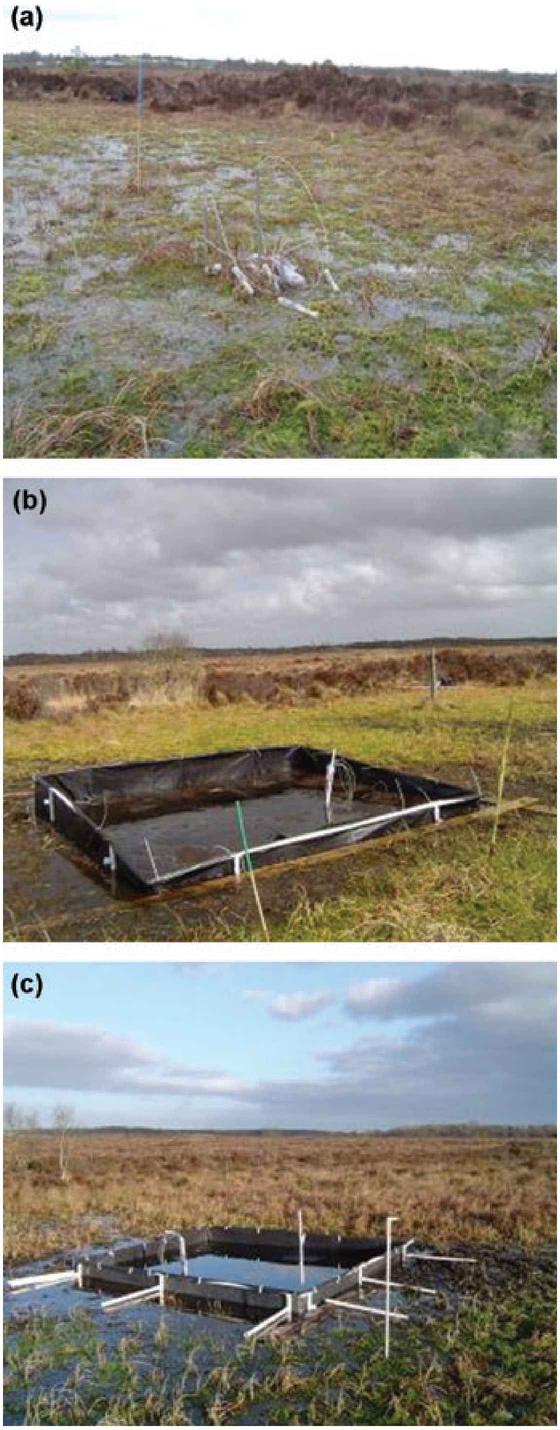

Figure 2. Photographs showing the three different treatments applied to experimental plots: (a) control, (b) permeable, and (c) enclosed.

all CH_4, CO_2, and O_2 from the substrate and headspace. The flasks were then kept in the dark at 18°C, and CH_4 concentrations in the headspace were measured twice a week, over a period of 3 weeks. The CH_4 production rates were calculated by linear regression of the measurements and expressed on a dry weight basis.

Temperature Monitoring

Temperature was monitored at different depths from two treatments, control and enclosed. Temperature loggers (HOBO Water Temp Pro: accuracy +/−0.2°C at 25°C) were installed at various depths below the surface (0.5, 1.25, and 2 m) and programmed to record peat temperature at 4-hour intervals. Loggers were deployed during December 2003 and data was downloaded during August–July 2005.

Results

Water Chemistry

At the surface and 0.5 m depth, pH and alkalinity were higher within the enclosed plots than the permeable plots, which in turn were higher than pH and alkalinity recorded from the control (Fig. 3). In all plots, pH, alkalinity, and calcium content increased with depth, and at 1 m, no consistent differences between treatments were evident indicating that the treatments did not have a major effect on water chemistry at depths greater than 0.5 m (Fig. 3).

It is most likely that water chemistry at the surface has the greatest influence on the vegetation development within plots. At the surface, pH, alkalinity, and calcium content of treated plots were all higher compared to the control plots (Fig. 3). Both control plots had a pH of less than 4.5 while the treated plots all had a mean pH of greater than 5. Both enclosed plots had a somewhat higher pH, alkalinity, and calcium content than the plots with the permeable treatment applied. Methane concentrations were highest within the permeable treated plots (Fig. 4a), while concentrations were comparable amongst the other treatments. Carbon dioxide concentrations are somewhat lower within the enclosed plots (Fig. 4b).

Vegetation Development

Before the experimental treatments, at all plots, the vegetation was similar, being dominated by *Sphagnum* mosses with sedge and herb species such as *Carex rostrata*, *Menyanthes trifoliata*, and *Hydrocotyle vulgaris* abundant.

Vegetation of Control Treatment. The vegetation of the control treatment resembles that which occurred throughout the entire area before the experiment being established and changes little throughout the monitoring period, although *Nuphar lutea* disappeared over the duration of the experiment (Table 1).

Vegetation of Permeable Treatment. A floating layer of highly decomposed peat developed at the surface of both plots 8 months following excavation. Initially, the floating peat layer was colonized by *Carex rostrata* and *Salix aurita*. Gradually, a greater number of species became established and within 3 years *Sphagnum fallax* dominated the vegetation covering approximately 70%. Notable additions to the vegetation of the permeable treatment include *Sparganium erectum* and *Typha latifolia* (Table 1).

Table 1. Estimated average percent cover of plant species of each treatment recorded in three subsequent years after treatments were applied.

Treatment	*Control*			*Permeable*			*Enclosed*		
Year (July)	*2004*	*2005*	*2006*	*2004*	*2005*	*2006*	*2004*	*2005*	*2006*
Vaccinium oxycoccos	1	—	—	—	—	—	—	—	—
Agrostis canina	2	3	3	—	—	—	—	—	—
Eriophorum angustifolium	3	3	3	—	—	3	—	—	—
Menyanthes trifoliata	5	5	6	—	—	—	—	—	—
Potentilla palustris	3	3	3	—	—	1	—	—	—
Sphagnum squarrosum	6	6	6	—	1	4	—	—	—
Anthoxanthum odoratum	—	—	1	—	—	—	—	—	—
Nuphar lutea	2	1	—	—	—	—	—	—	—
Eriophorum vaginatum	1	1	3	—	1	1	—	—	—
Carex rostrata	3	4	3	3	6	4	1	—	—
Sphagnum fallax	7	7	7	2	5	7	1	—	—
Hydrocotyle vulgaris	2	1	3	—	3	3	—	—	—
Holcus lanatus	2	1	2	—	3	3	—	—	—
Salix aurita	2	—	—	2	3	3	2	—	—
Aulacomnium palustre	—	—	—	—	1	1	—	—	—
Epilobium sp.	—	—	—	—	3	2	—	—	—
Juncus effusus	—	—	—	—	4	5	—	—	—
Polytrichum commune	—	—	—	—	1	—	—	—	—
Sparganium erectum	—	—	—	1	4	3	—	—	—
Typha latifolia	—	—	—	—	1	2	—	—	—
Warnstorfia fluitans	—	—	3	—	1	3	—	—	—
Utricularia minor	—	—	—	—	—	—	4	6	2
Potamogeton natans	—	—	—	—	—	—	—	2	6
Aquatic plants (%)	<5	<5	0	0	0	0	5	25	35
Bryophytes (%)	95	100	95	<5	20	70	0	0	0
Herbs (%)	30	25	50	5	45	40	<5	0	0
Total vegetation cover (%)	100	100	100	5	55	85	5	25	35

Cover abundance values: 1 (1–2 plants, cover <5%), 2 (25–100 plants, cover <5%), 3 (>100 plants, <5% cover), 4 (5–12% cover), 5 (13–25% cover), 6 (26–50% cover), 7 (51–75% cover), and 8 (76–100% cover).

Vegetation of Enclosed Treatment. Vegetation development differed considerably to that recorded in the permeable plots. Despite a temporary occurrence of floating peat within the first year, these plots remained aquatic throughout the remainder of the study period. Within 2 years *Utricularia minor* occurred throughout, following this, *Potamogeton natans* (a species only previously recorded at the site in 1978) became established and within 3 years covered approximately 35% (Table 1).

Methane Production

Our results show that peat substrate from the permeable treatment had a much greater potential methane production rate than the peat substrate from either the control or the enclosed treatment (Fig. 4c).

The methane production rates indicate that the substrate of the permeable plots contains more reactive carbon which can be converted to methane. A potential source of this carbon is the occurrence of reactive dissolved carbon in the form of DOC from the actively growing surrounding scragh. This input of carbon may be absent from the enclosed plots. Our results confirm that the permeable and control plots contained a higher concentration of DOC in the top layer (circa 0.5 m depth) than the enclosed plots (Fig. 4d).

Temperature Monitoring

Figure 5 shows the temperature duration curves of the water/peat at 0.5, 1.25, and 2 m depth from both a control plot and an enclosed plot during summer and winter. There are clear differences in the temperature regimes between the different treatments. During the summer, temperature within the enclosed treatment is greater than 15°C for over 55% of the time whereas in the control, temperature never exceeded 15°C. In contrast, during winter the temperature within the enclosed treatment is considerably lower than that recorded within the control. These differences are also evident at greater depths although less pronounced.

Discussion

Restoration Potential of Lough Roe Soak

The results of hydrochemical monitoring show that by removing the floating raft, the chemistry of pore water in the upper meter changes to become more alkaline, with a higher pH and calcium content. The cause of the increased alkalinity recorded within the excavated plots is likely to partly result from the absence of *Sphagnum* sp., which are capable of bringing about acidification of solutions in which they are

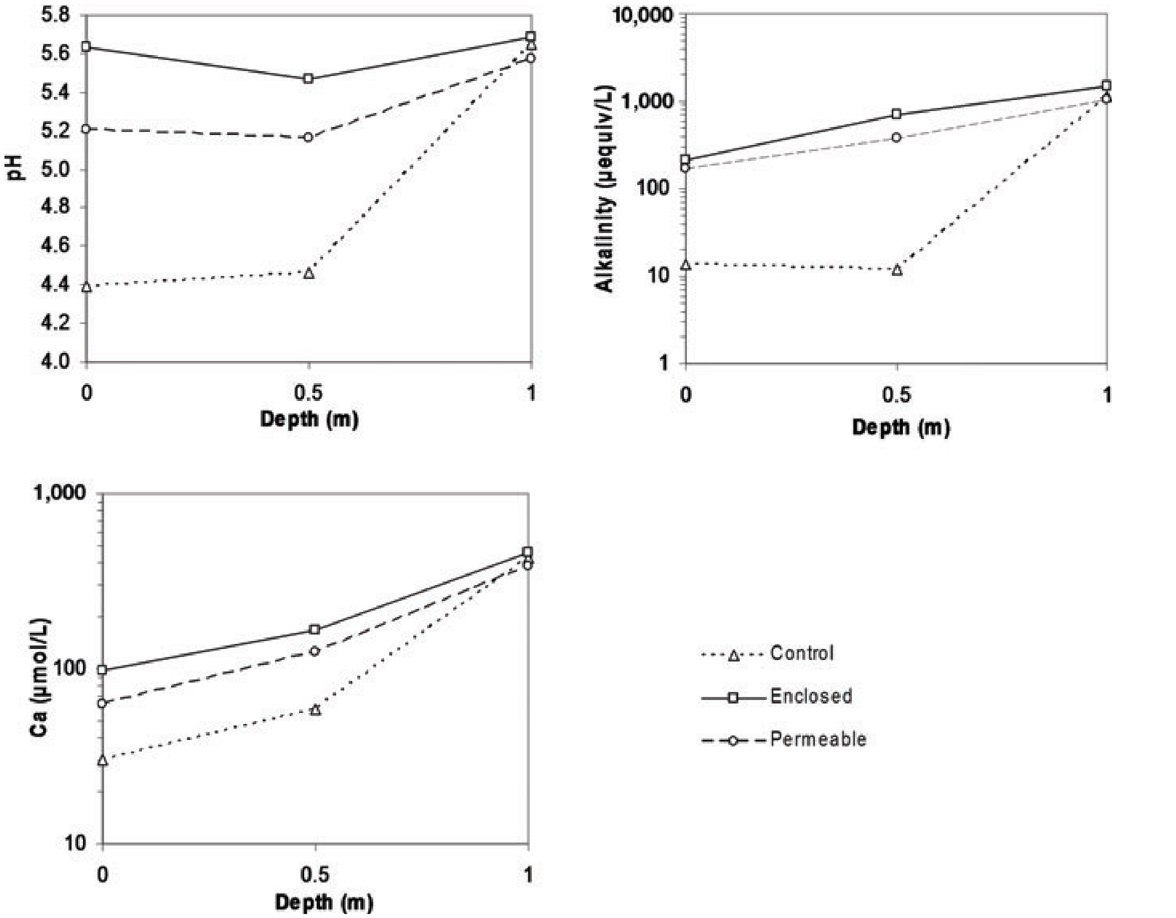

Figure 3. Average pH, alkalinity, and calcium concentration of pore water at the surface, 0.5 and 1 m depth of each treatment ($n = 2$, sampled on 13 dates).

growing by the uptake of cations and release of equivalent numbers of hydrogen ions (Clymo 1963; van Breemen 1995). Furthermore, some improved exchange with deeper, more alkaline water could have occurred due to wind and wave action.

Differences between the permeable and enclosed treatments were apparent in both surface water chemistry and vegetation development. The most notable difference was the appearance within 1 year of floating peat across the entire surface of both permeable plots. Other studies have shown that methane bubbles trapped in the peat are involved in the buoyancy of peat substrates (Lamers et al. 1999; Scott et al. 1999; Tomassen et al. 2003). Increased pH is known to enhance methane production by stimulating the activity of methanogenic bacteria (Williams & Crawford 1984; Dunfield et al. 1993; Segers 1998), and increased temperature is known to have a similar effect (Dunfield et al. 1993; Bergman et al. 1998). Tomassen et al. (2003) have already shown that an increase of pH by one unit (e.g., from 4 to 5) could strongly increase methane production and result in peat becoming buoyant. In addition, the development of floating peat has been shown to depend on the physical and chemical properties of the peat (Smolders et al. 2002; Strack et al. 2006). Based on the homogeneity of the peat substrate throughout all plots and the proximity of the treatments to each other within the soak, it is unlikely that peat quality was a factor in the current study. Similarly, there are no indications that pH and temperature differences would explain differences in methane production between the treatments which involved raft removal. The availability of easily degradable compounds, such as root exudates, is important for methanogenic bacteria (Bergman et al. 2000; Tomassen et al. 2004). The pore water of the surrounding scragh is likely to contain relatively high quantities of these compounds, as indicated by the higher concentration of DOC recorded in both the control plots and the permeable plots. However, it is well known that decomposition of organic matter and methanogenesis is inhibited in acid systems compared with alkaline waters (Mc Kinley & Vestal 1982; Kok & van der Laar 1991; Lamers et al. 1999; Smolders et al. 2002). Therefore, despite the high DOC levels in the raft (control treatment) methanogenesis is low due to the low pH of the pore water. We conclude that this supply of easily degradable material in combination with the relatively high pH and increased temperature is the most likely explanation for higher methane

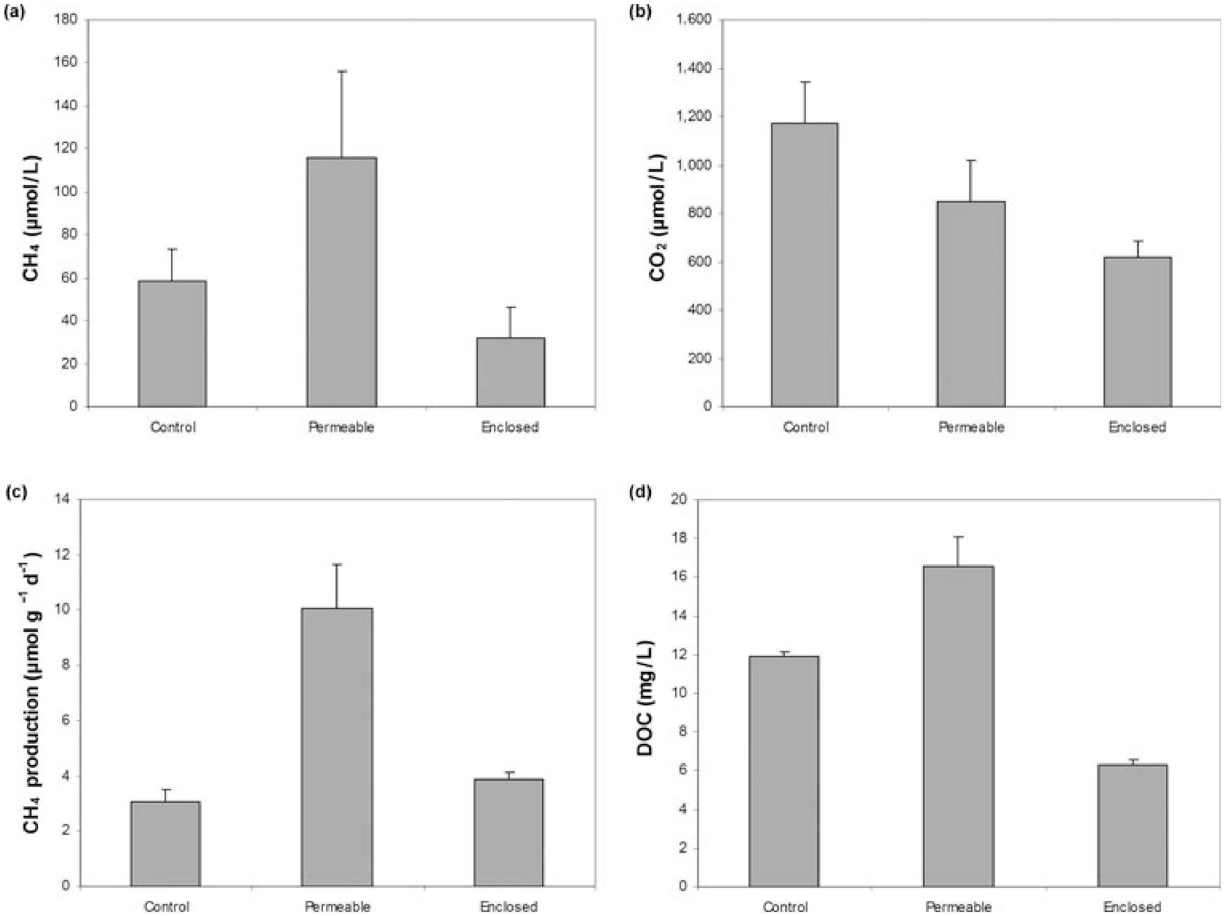

Figure 4. Mean CH_4 (a) and CO_2 (b) concentration of pore water at the surface of different treatments (error bars = standard error of the mean, $n = 2$ sampled on 13 dates). Mean CH_4 production rates (c) in the peat substrate and mean concentration of dissolved organic carbon (d) in pore water at 0.5 m from the different treatments (error bars = standard error of the mean, $n = 2$).

production rates and in turn floating peat development within the permeable plots.

The floating peat proved suitable for the rapid colonization by species that occur on the surrounding scragh including *Carex rostrata* and *Sphagnum fallax* forming a vegetation type broadly similar to that which occurs in the surroundings as represented by the control plots. Floating rafts remain in contact with fluctuating water tables throughout the year, and therefore offer excellent opportunities for *Sphagnum* sp. to regenerate (Campeau & Rochefort 1996; Smolders et al. 2003). The presence of *Typha latifolia* and *Sparganium erectum* are notable additions to the flora, both were previously recorded in the area in 1992 (Connolly et al. 2002) but by 2003 had become locally extinct (Crushell et al. 2006). The occurrence of these species shows that once suitable conditions occur, it is possible for locally extinct species to reappear, depending on their ability to lie dormant in the peat/scragh or disperse from areas where they continue to occur in the surrounding landscape. The abundance of *Juncus effusus* on the floating peat is likely to reflect the availability of nutrients (P, N, and K) as recorded elsewhere by Tomassen et al. (2003), and also the initial absence of *Sphagnum*. The presence of *Sphagnum* mosses has the effect of immobilizing most of the nutrients supplied from the atmosphere and thereby restricts vascular plants to nutrients available from mineralization processes in the peat layer; in addition *Sphagnum* presence has the added effect of restricting such mineralization (e.g., Malmer et al. 1994; Lamers et al. 2000). *Juncus effusus* and other vascular plants are therefore likely to diminish as *Sphagnum* becomes more established. This may also partly explain the initial success followed by a sharp decline of *Salix aurita* seedlings recorded.

Three years following excavation, the enclosed plots had habitat characteristics and vegetation similar to that recorded in 1978 when the last remnant of open water with *Potamogeton natans* was recorded (Crushell 2008). The reappearance of *Potamogeton natans* may show its ability to lie dormant, its occurrence is also indicative of the relatively base rich conditions. The temporary dominance of *Utricularia minor* was also recorded by other researchers within 2 years of sod removal from an acidified rich-fen (Beltman et al. 1995).

The increased alkalinity and calcium content of surface water recorded within the enclosed plots compared with the permeable plots is most likely to result from the exclusion

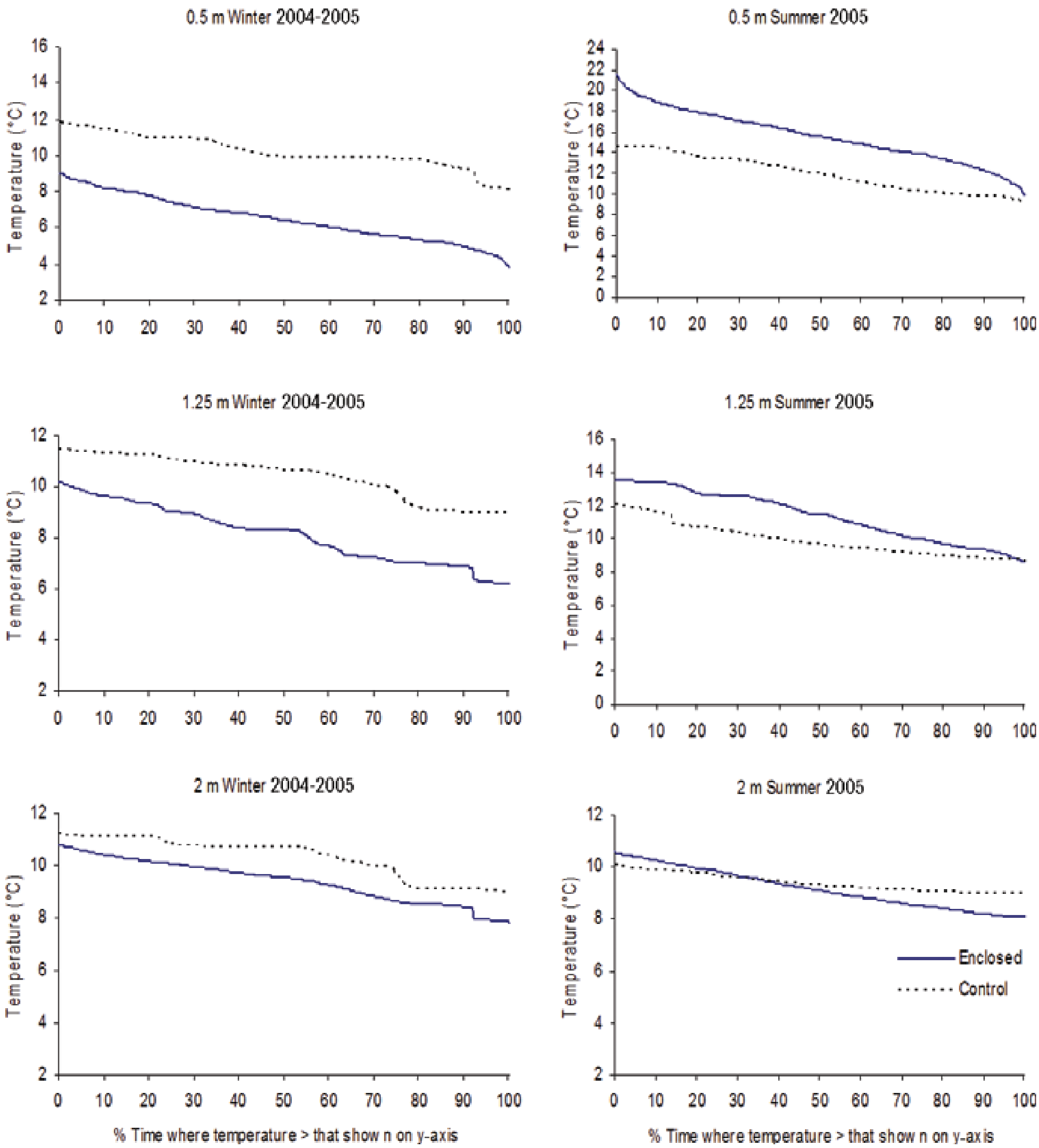

Figure 5. Temperature duration curves for the enclosed and control treatments at various depths during summer 2004 (1 May–31 July) and winter 2004–2005 (1 November–31 January).

of acid water influence from the surrounding scragh. In combination with this, some improved exchange with deeper, more alkaline water would have occurred due to disturbance by wind. Such mixing would have been prevented as soon as a complete floating peat layer developed within the permeable plots.

Terrestrialization and Acidification of Lough Roe Soak

The findings of the current study may aid in interpreting the initial cause and sequence of terrestrialization over the past century. We suggest the following hypothesis as illustrated in Figure 6 to explain the rapid transformation of Lough Roe from a minerotrophic lake at the beginning of the twentieth century (Fig. 6a) to a semiterrestrial fen system for much of the twentieth century (Fig. 6b) to a terrestrial ombrotrophic system by the beginning of the twenty-first century (Fig. 6c).

During the nineteenth century, human impacts increased throughout the bog commencing with the construction of a road and associated drainage across the bog circa 1800; a drain leading from Lough Roe toward the road was later inserted circa 1850 (Crushell et al. 2008). Resulting from the various human impacts, the bog surface subsided by a minimum of 2 m in the vicinity of Lough Roe (van der Schaaf 2002). This subsidence caused the catchment divide of the bog dome to move northwards from the soak (van der Schaaf 2002).

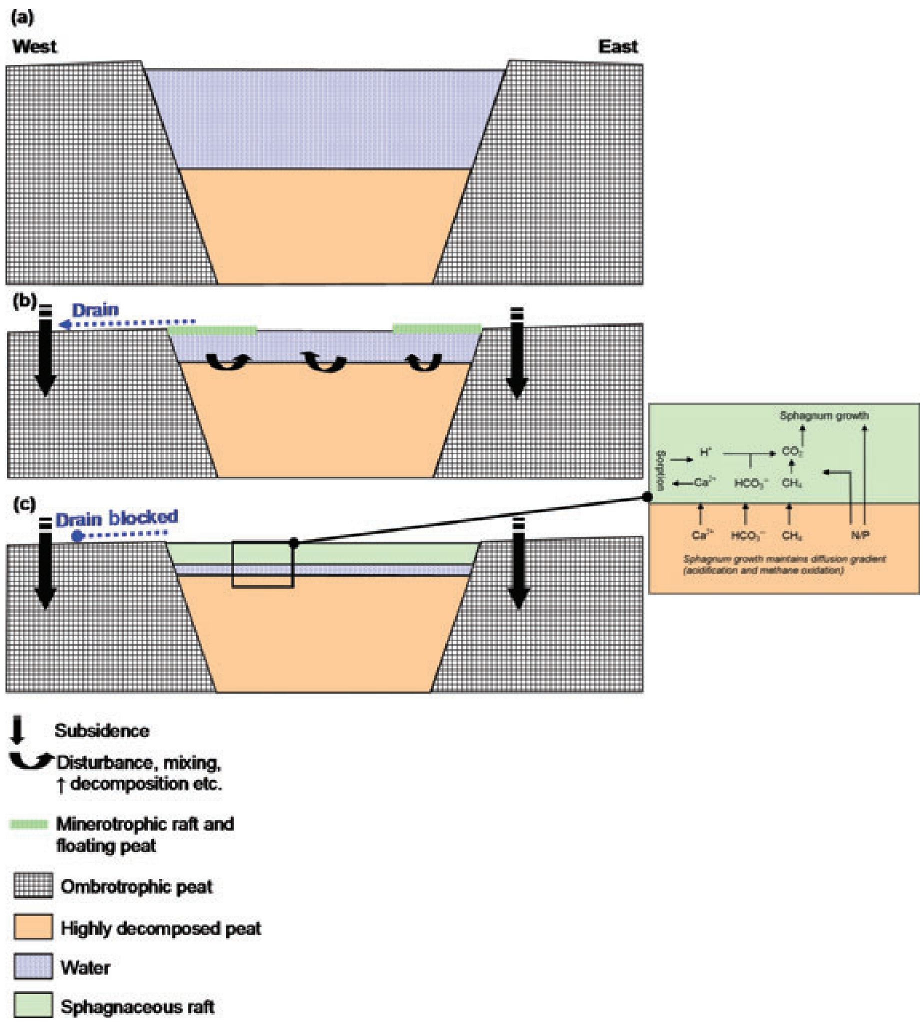

Figure 6. Schematic diagram showing the three major stages in the terrestrialization and subsequent acidification of Lough Roe since circa 1900. (a) Prior to 1800, relatively deep water, with minerotrophic characteristics. Likely that fen vegetation grew around the margin of the lake with floating macrophytes across much of its surface. The lake was close to the topographical high point on the bog dome and therefore little surface water influence from surrounding bog. (b) Circa 1912, following major human disturbance subsidence and drainage causes lake to become shallower and more influenced by acid bog water from the surroundings as the catchment divide of the bog shifts northwards. A floating raft gradually develops from the margins, which may have in places originated from floating peat due to increased decomposition and methane production in the upper layer of substrate. Vegetation has strong minerotrophic characteristics due to minerotrophic nature of the substrate and underlying water. (c) Circa 2003, drain leading from Lough Roe has been blocked allowing development of rainwater lenses and floating raft has become thicker. The surface has become more isolated from the underlying minerotrophic conditions. *Sphagnum* expands, and conditions become more suitable for ombrotrophic species.

The subsidence coupled with the direct effect of drainage on the soak caused a likely reduction of the depth of water overlying the highly decomposed peat from over 2 m to less than 1 m (based on the depth of the old drain leading from Lough Roe and estimated subsidence). Following the changes in hydrology and topography, a combination of the following factors would have facilitated a floating minerotrophic scragh to develop over the surface of the lake.

First, shallow conditions would have allowed floating macrophytes to root in the substrate of the lake and acquire nutrients from the minerotrophic substrate. Second, decomposition would have increased in the upper layers of this substrate due to an increase in temperature during summer (present study recorded temperatures up to 10°C higher during summer at 0.5 m depth compared with 2 m depth), higher availability of oxygen in the upper layer of substrate due to disturbances such as wind and wave action, and an increased input of dissolved reactive carbon from surrounding bog water (Smolders et al. 2003) passing through the surface of the lake. The increased rates of decomposition would have produced a higher concentration of methane, which may have provided buoyancy to the peat substrate thereby forming floating rafts as reported in the current study.

The chemistry of this lake substrate is comparable to peat formed under the influence of calcareous groundwater (Crushell et al. 2009). It is likely that phanerograms and brown mosses typical of fen conditions were the major components of the minerotrophic raft as described from areas within the site in 1978 (Crushell 2008). In the initial stages of raft development, *Sphagnum* growth is likely to have been limited because of relatively high pH and calcium concentration as such conditions are known to restrict the growth of *Sphagnum* (Clymo 1973; Money 1995).

We suggest that such floating peat formation would have initially only occurred in isolated patches around the edges of the soak where local conditions were suitable. This could explain the gradual terrestrialization of the soak from the edges as is known to have been the case (Crushell et al. 2008). The floating nymphoid vegetation of the lake center became gradually replaced by the floating raft as it encroached across the surface until finally by the early 1990s the raft covered the entire former lake surface.

As the minerotrophic raft proceeded across the lake surface and became progressively thicker, the surface gradually became more isolated from the underlying mineral rich conditions and thus more influenced by acid rainwater (van Diggelen et al. 1996). *Sphagnum* sp. suited to higher pH conditions such as *Sphagnum squarrosum* and *Sphagnum fallax* would have become established and in turn caused further acidification (Mälson et al. 2008). Gradually, ombrotrophic species moved in and the more minerotrophic species declined as reported from the site during the period 1978–2003, by which time true ombrotrophic communities had established around the margins of the former lake (Connolly et al. 2002; Crushell et al. 2006). During this period (circa 1985), the drain leading from the soak was blocked as a management measure aimed at preventing further drying out of the surrounding bog. The blocking of the drain is likely to have had the effect of further acidifying the surface of the lough by increasing the influence of rainwater and surface bog water from the surroundings.

Conclusion

The objective of wetland restoration is to bring a wetland back to a former condition (Wheeler 1995). In the case of Lough Roe, restoration may aim to either (1) return the site to an open water lake (with fringing fen vegetation) that was present at the site prior to major human impact or alternatively (2) to restore the floristically interesting minerotrophic raft that was present for much of the twentieth century. Below we present how either option could be achieved; however, local stakeholders need to decide on which option is most desirable.

It may be possible to achieve (1) by removing the floating sphagnaceous raft from the surface while at the same time manipulating the local hydrology to prevent a through-flow of surface bog water from the surroundings. As an additional measure, dredging of the peat substrate within the opened area should be considered. A greater depth of water would more closely imitate the conditions before subsidence of the bog and would create an environment less suitable to terrestrializing plants and floating peat formation.

To achieve this condition (2), it would again be necessary to remove the scragh from the surface of the lough. It would not be necessary to isolate the area from surrounding surface bog water. It is likely that floating peat rafts would form and this relatively mineral rich material would suit the establishment of fen plants that were present in the area before acidification. As an additional measure, it may be necessary to allow surface rainwater to discharge from the area thereby preventing the development of rainwater lenses and rapid acidification of the surface again. This measure would imitate the effect of the drain leading from Lough Roe, which probably slowed down acidification of the surface until it was blocked during the 1980s.

In a broader context, our results can be applied to the more widespread practice aimed at restoring bog vegetation. Despite the fact that over 60,000 ha of industrial cut-away bog occurs in Ireland, restoration of true bog vegetation on these sites has not yet been attempted (Foss et al. 2001; Farrell 2008). A common method of restoring such areas is inundation with the objective of floating peat rafts forming, upon which bog vegetation would establish. Peat bog restoration is usually assumed to be a slow process involving long time spans (Joosten 1995), although some researchers have shown otherwise (Rochefort et al. 2003). Our results show that under alkaline conditions floating peat can occur rapidly and that these peat mats can develop into *Sphagnum*-dominated vegetation in a time span of only a few years. A prerequisite for such a rapid development of a functional acrotelm (the living layer at the surface of a bog usually dominated by *Sphagnum* mosses) is that the top layer of the floating peat becomes acidic. A steep gradient of an acidic top layer on an alkaline lower layer results in an extra supply of carbon dioxide which favors *Sphagnum* growth (Smolders et al. 2003).

Implications for Practice

- To restore and maintain aquatic successional stages in soak or fen situations, it may be necessary to manipulate the hydrology of the surroundings to prevent influence of acid water at the surface.
- In restoring bog vegetation on cut-away peatlands by inundation it is beneficial to have floating peat formation. The ideal situation for the formation of such peat rafts is an acid top layer on an alkaline lower layer. Therefore, it may be less difficult to initiate bog vegetation in a fen or groundwater fed situation rather than within a completely acid/ombrotrophic environment.
- In suitable conditions, it is possible for a floating peat layer to develop a complete *Sphagnum*-dominated raft within 3 years. Among other things, the presence of a seed bank and suitable vegetation in the surroundings is of high importance. In the restoration of soaks or wetlands, it is important to define which former stage is to be restored. In the case of Lough Roe soak this could be the former stable open water phase or the more floristically interesting but unstable floating raft with an abundance of minerotrophic species.

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