Restoration techniques for *Sphagnum*-dominated peatlands

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Abstract: Ombrotrophic peatlands in North America are harvested mainly for horticultural purposes. Following intense exploitation, these peatlands are generally abandoned to natural regeneration. The abandoned sites usually remain barren or poorly revegetated by a few vascular plants for several years. The post-harvested sites are not usually recolonized by *Sphagnum* species (peat mosses), which are the key species to restore peatland functions. The objective of this study was to develop restoration techniques for post-harvested peatlands. The experiments centred on *Sphagnum* reintroduction, since peat mosses are responsible for peat accumulation. Vegetative *Sphagnum* fragments were used as diaspores. Various methods of *Sphagnum* reintroduction were tested to ensure reliable colonization. A microrelief formed of ridges and depressions provided humid conditions in depressions which favored *Sphagnum* establishment. Reintroducing *Sphagnum* diaspores in combination with such companion plant species as *Eriophorum angustifolium* also had a positive effect on the survival of peat mosses. A phosphorus amendment led to improved establishment of Sphagna and companion plant species.

Key words: *Sphagnum*, microtopography, companion species, phosphorus, fertilization.

Résumé : Les tourbières ombrotrophes sont des types de milieux humides exploités en Amérique du Nord pour des fins principalement horticoles. Au terme de l'exploitation, ces tourbières sont généralement abandonnées à la régénération naturelle. Les sites abandonnés demeurent le plus souvent dénudés ou faiblement revégétés par certaines plantes vasculaires et ce, même après de nombreuses années. Ils ne sont généralement pas recolonisés par les sphaignes qui sont la végétation clé pour restaurer les fonctions des tourbières. L'objectif de cette étude était de développer des techniques de restauration des tourbières abandonnées après exploitation. Les expériences ont porté sur la réintroduction des sphaignes qui sont les plantes responsables de l'accumulation des dépôts de tourbe. Des fragments végétatifs de sphaignes ont été utilisés comme diaspores. En vue d'assurer de meilleures chances de réimplantation des sphaignes, diverses méthodes ont été testées. La création d'un microrelief formé de buttes et de dépressions a fourni des conditions plus humides dans les dépressions, ce qui a favorisé l'établissement des sphaignes. La présence de plantes-abri bien établies tels les *Eriophorum angustifolium*, en association avec les diaspores de sphaignes, a eu un effet positif sur la survie de ces mousses. Une fertilisation de phosphore a conduit à une meilleure réimplantation des sphaignes et des plantes compagnes.

Mots clés : Sphaignes, microrelief, plantes compagnes, phosphore, fertilisation.

Introduction

Exploitation of ombrotrophic peatlands, or bogs, by the vacuum method for horticultural *Sphagnum* peat causes major disturbances to these wetland ecosystems. Peatlands are drained and the vegetation is completely removed. Following years of peat-harvesting activities, the barren fields are generally simply abandoned. These harvested peat fields have lost all their viable seed bank (Salonen 1987) and depend on the seed rain for their natural revegetation. However, natural regrowth by *Sphagnum*, the peat mosses responsible for peat accumulation and formation of bogs, does not generally occur, even after many years of abandonment (Poschlod 1992; Lavoie and Rochefort 1996). Normally, these sites can only be recolonized by vascular plants that tolerate the dry and acidic conditions of the substratum.

The reestablishment of *Sphagnum*-based vegetation on post-harvested fields is a desirable aim for ombrotrophic peatlands restoration (Wheeler and Shaw 1995) because it is a necessary step to restore ecological values such as water filtration, carbon storage, and wildlife habitat. To achieve this goal, we chose the approach of actively reintroducing *Sphagnum* diaspores (i.e., whole *Sphagnum* plants cut in fragments) from natural peatlands to exploited peatlands, as it appears to be a promising method for reestablishing moss carpets on denuded peat (Bastien 1996; Campeau and Rochefort 1996; Quinty and Rochefort 1997).

Sphagna are ectohydric mosses that require a humid environment for their survival and growth (Chopra and Kumra 1989). As a result, the rewetting of abandoned peat and maintenance of humid conditions have been identified as key factors in the reestablishment of peat mosses. Unfortunately, the water table during the growing season can recede too low (i.e., lower than 40 cm below the peat surface) to support

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the growth of *Sphagnum* species, even after rewetting the formerly drained sites by damming the ditches (Schouwenaars 1988). For successful restoration, active steps to recreate favorable moisture conditions of the substrata are warranted. Therefore, any interventions that help to create enhanced humidity of the peat–air interface should allow better survival of the reintroduced mosses.

Increasing the roughness of the flat abandoned peat fields has been suggested by Eggelsmann (1988) as a method to enhance moisture conditions at the peat surface. For natural revegetation, he has recommended the creation of artificial hummock–hollow complexes with a light plough to create depressions that hold back water and hummocks that serve as wind shelters. Reintroducing *Sphagnum* with companion plant species is another alternative to create a more favorable, humid microclimate. Salonen (1992) showed experimentally that more plants have naturally recolonized barren peat fields under artificial plant covers than on bare peat. He associated this improved recolonization with increased moisture conditions and lower temperatures at the peat surface created by the artificial plant cover.

When the main factors restricting revegetation have been identified, complementary methods can be researched to accelerate reestablishment of the vegetation. Fertilization in a restoration perspective could be a method to increase the availability of nutrients and favor the establishment of reintroduced vegetation. Ombrotophic peatlands are nutrient-poor environments (Gorham et al. 1985; Damman 1987), and phosphorus seems to be one element that particularly restricts plant productivity in peatlands (Tamm 1954; O'Toole and Synott 1971; Brown 1982). Therefore, a light phosphorus application could be advantageous for restoration.

To restore a peat-accumulating system on a formerly harvested peatland, three factors were tested with the aim of facilitating the establishment of a peat moss carpet. The general approach was to take *Sphagnum* diaspores from a bog, broadcast them on the bare peat fields, and protect them against adverse environmental conditions to ensure better survival. The factors considered were (*i*) microrelief: depressions and ridges were created and compared with the flat surfaces normally left after exploitation; (*ii*) companion plant species: three groups of companion species were reimplanted in association with *Sphagnum* diaspores and were compared with a control of *Sphagnum* diaspores only; (*iii*) fertilization: a light phosphorus fertilization was applied and compared with a control.

Methods

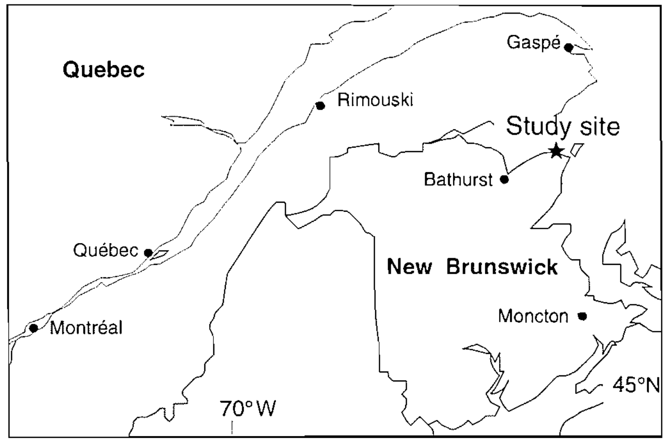
Study area

The experiments were conducted at Maisonnette (Fig. 1), New Brunswick (47°49′15″N, 62°02′15″W). Local mean annual temperature is 3.3°C, and mean annual precipitation is 1017 mm, of which 710 mm is rainfall (Environment Canada 1993).

The experimental site is located in the coastal oceanic bog zone (Zoltai 1988) and covers 541 ha. About 340 ha are currently harvested for horticultural peat. In summer 1992, a 2.16-ha portion of the peatland was set aside as a study site for restoration practices. Thickness of the residual organic layer varies between 40 and 120 cm, of which the first 10–30 cm is *Sphagnum* peat.

In August 1992, the main perimeter drainage ditches of the study site were filled with in situ peat and leveled to allow rewetting. In the fall of 1992, a series of 35 water wells were installed to monitor water table fluctuations. These wells were made of 5 cm diameter PVC pipes and were distributed over the site to cover topographic gradients.

Fig. 1. Location of the study site at Maisonnette in New Brunswick.



Water chemistry parameters were monitored in 1992, 1993, and 1994. To collect water samples, a series of pits (40 × 40 cm) were dug at the study site to an approximate depth of 10 cm above mineral soil. Four more pits were also dug in a natural, nonharvested area of the peatland. Samples from the experimental and natural sites were taken in October 1992, May 1993, and May 1994. Samples were filtered through a 0.45-μm acetate filter prior to analysis. Conductivity measurements were corrected for temperature and pH according to Sjörs (1950). NH_4-N values were obtained by steam distillation. Base cations (Ca, Mg, K, Na) were measured by atomic absorption. Ionic chromatography techniques were used to determine Cl, NO_3, and SO_4 levels. Total P levels were determined by colorimetry.

Creation of a varied microrelief, introduction of *Sphagnum* diaspores with companion plant species, and phosphorus application

The study was carried out with a split – split-plot experiment in a completely randomized design. Six main plots of 40 × 40 m were delimited for the microrelief. Each main plot was divided into four subplots for the reintroduction of *Sphagnum* diaspores and companion plant species. Each subplot was subdivided in two sub-subplots of 2.5 × 5 m separated from each other by a 5-m buffer zone. The sub-subplots were used for the amendment trials.

Microrelief

Surface roughness was created by the passage of an excavator in three main plots. The resulting microrelief consisted of a parallel series of shallow depressions (excavator tracks 50–70 cm wide and approximately 15 cm deep) bordered by ridges (50–80 cm). The three other main plots remained undisturbed and level.

Sphagnum *and companion plant species*

The choice of *Sphagnum* and companion plant species was made according to both their potential to establish on ombrotrophic or poor fen substratum and their local availability. The four species chosen (*S. magellanicum* Brid., *S. flavicomans* (Card.) Warnst., *S. fuscum* (Schimp.) Klinggr., and *S. capillifolium* (Ehrh.) Hedw.) are known to occur naturally within the range of water-chemical conditions observed at the experimental site (Table 1). *Sphagnum* species were also chosen according to their ability to establish on

Table 1. Water chemistry values for the Maisonnette experimental and natural sites for three years (1992–1994).

Water chemistry	Natural site	Experimental site
No. of samples	10	45
pH	3.9–4.1	3.5–4.1
Conductivity (μs at 20°C)	0–60	23–136
Cations		
Ca (mg/L)	0.2–0.6	<0.05–1.36
Mg (mg/L)	0.2–0.6	0.4–4.9
K (mg/L)	0.1–0.4	0.3–4.2
Na (mg/L)	2–8	3–22
Cl (mg/L)	5–10	7–26
SO_4 (mg/L)	1–3	2–25
NH_4-N (mg/L)	<0.5–2.8	1–16
NO_3-N (mg/L)	<0.05–<0.5	<0.05–1.7
P total (mg/L)	<0.02–0.04	<0.009–0.35

Note: Values range from minimum to maximum.

drier or wetter microhabitats, the rationale being that even though the Sphagna are reintroduced in a mixture (see below), the species that normally occupy the wettest microhabitats (e.g., *S. magellanicum*) should be favored by the conditions recreated in the depressions, whereas one would expect only the drier species to colonize the drier ridges. Because one aim of this research is the eventual scaling up of peatland restoration techniques, the reintroduction of regionally dominant species appears to be an optimal approach to rapidly colonize all the empty niches of the post-harvested field. To test the effect of companion species on the establishment of *Sphagnum*, three plant groups were selected: ericaceous shrubs, herbaceous plants, and brown mosses. These companion plants were reintroduced in combination with *Sphagnum* diaspores and were compared to a control that received only *Sphagnum* fragments. Companion species were introduced a year before the introduction of *Sphagnum* diaspores, i.e., in May and June 1993. Four ericaceous shrubs were chosen: *Ledum goenlandicum* Oeder, *Kalmia angustifolia* L., *Chamaedaphne calyculata* (L.) Moench, and *Andromeda glaucophylla* Link. Ericaceous shrubs were hand collected in the nearby natural peatland and transplanted with a 50-cm spacing for a total of 50 plants/12.5 m^2. *Eriophorum angustifolium* Honckeny, or cotton grass, which is a graminoid species that propagates rapidly via rhizomes, was chosen as the herbaceous species. Plants with rhizomes were collected at the edge of the exploited sections, and a total of 50 plants/12.5 m^2 was transplanted. All these companion plants were transplanted on both depressions and ridges. The reintroduced brown mosses were *Dicranum undulatum* Brid. and *Polytrichum strictum* Brid. Whole individual moss plants of about 3–5 cm size were hand collected and hand spread fresh at a ratio of 300 plants/m^2.

Sphagnum fragments were introduced in May 1994. A collection to spreading ratio of 1:20 was chosen as suggested by Campeau and Rochefort (1996) as a density offering a good compromise between good establishment and the need to minimize the impact on natural bogs where *Sphagnum* species are collected. This ratio means that 1 m^2 of collected peat mosses is spread over 20 m^2 of abandoned surface. For all plots, the mixture of *Sphagnum* species was the same and consisted of *S. magellanicum*, *S. flavicomans*, *S. fuscum*, and *S. capillifolium*. Sphagnum plants were hand collected to a depth of 10 cm in monospecific patches from a bog. *Sphagnum* plants were cut into 2-cm fragments to multiply the number of diaspores, as *Sphagnum* has a great ability to reproduce vegetatively from fragments (e.g., Rochefort et al. 1995). Fragments of the four species were hand mixed and hand spread on each plot.

Phosphorus amendment

In June 1993, half plots of vascular plants were fertilized with granular triphosphate (0:46:0 N–P–K) at a concentration of 50 g/m^2. In May 1994, the sub-subplots were slightly refertilized when the *Sphagnum* diaspores were introduced. This time, a 6-ppm liquid solution was prepared from ground granular triphosphate. Fertilization was applied with a pulverizer at a rate of 2.4 mg/m^2.

Evaluation of vegetation reestablishment

At the end of September 1994, the recolonization success by the Sphagna and the companion species was evaluated. Capitula were counted, i.e., those introduced in spring and those newly formed during the growing season, and their percent cover esimated. A regenerant was considered as a new capitulum when at least three or four branches were developed and grouped in a head. The percent cover of companion mosses and vascular plants was evaluated. Six quadrats (30 × 30 cm) per flat sub-subplot and nine quadrats in sub-subplots with microrelief were counted. The quadrats were systematically located along two (flat sub-subplots) or three (increased microrelief sub-subplots) transect lines running perpendicularly to the lines of depressions and ridges.

Statistical analysis

Analyses of variance were carried out using the GLM procedure of SAS (SAS Institute Inc. 1988). Once a treatment effect was shown significant at the 0.05 level, a Tukey's test (Sokal and Rohlf 1981) was used to locate which level or levels of a treatment was significantly different from the other. Capitulum counts data were transformed ($(x + 0.5)^{1/2}$) prior to analysis to reduce heterogeneity of variances. The data for the percent cover of *Sphagnum* capitula, companion mosses, and vascular plants were analyzed untransformed.

Results

Sphagnum survival and establishment

Effect of microrelief

The increase in topography had no significant impact on *Sphagnum* establishment as represented by the average number of capitula ($p = 0.96$, Table 2; ridges and depressions pooled). However, the success of establishment according to the three microhabitats appears to differ. The results suggest that there is a potential for faster moss reestablishment in sheltered depressions (Fig. 2).

Effect of companion plant species

The presence of companion plant species had no significant impact on the number of capitula ($p = 0.53$, Table 2). However, the percent cover of Sphagna was significantly greater in the presence of companion species ($p = 0.04$, Table 2). This indicates the development of larger capitula under plant cover, which was confirmed by qualitative observations.

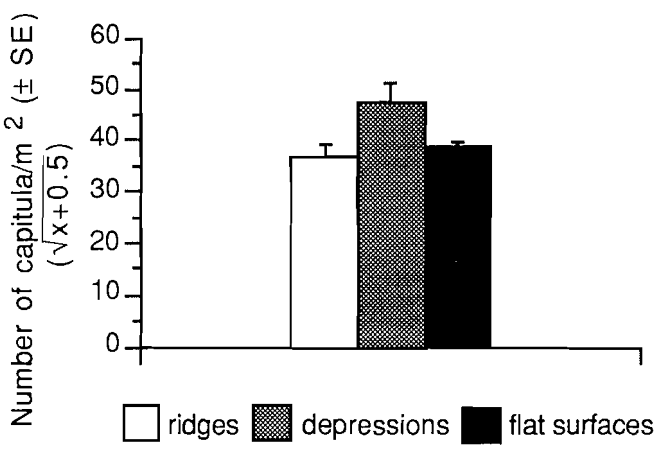
The establishment of vascular plants and other mosses showed variable success (Fig. 3). The relatively low number of ericaceous shrubs (E) that survived transplantation, their slow growth, and their low recovery after transplantation meant that they did not offer the protection expected. On the other hand, the propagation of *Eriophorum* took place readily, with cover increasing steadily from the beginning of the first growing season to the end of the second growing season. The *E. angustifolium* (H) were the companion species that led to the best recolonization of *Sphagnum* diaspores in terms of percent cover (Fig. 4). For companion mosses (M), the

Table 2. Analysis of variance on the effect of microrelief, companion species, and phosphorus fertilization on *Sphagnum* establishment on bare peat after one growing season (density ratio ≈ 1:20).

		No. of capitula		Percent cover	
Source of variation	df	Mean square	p	Mean square	p
Main plots					
Microrelief (M)	1	2.0	0.959	62.0	0.452
Error a	4	661.7		89.5	
Subplots					
Companion species (C)	3	31.8	0.531	33.5	0.043
M × C	3	38.7	0.452	4314.5	0.242
Error b	12	41.1		9.1	
Sub-subplots					
Amendments (A)	1	338.4	0.003	69.3	0.005
M × A	1	38.9	0.249	0.1	0.925
C × A	3	58.2	0.134	19.8	0.056
M × C × A	3	27.0	0.419	3.2	0.688
Error c	16	27.1		6.4	

Note: Capitula counts were transformed as $(x + 0.5)^{1/2}$.

Fig. 2. Comparison of *Sphagnum* recolonization between the ridges and depressions of the roughened surfaces and flat surfaces of the control from an introduction ratio of ~1:20 after one growing season.



implantation of *D. undulatum* proved unsuccessful, but *P. strictum* established readily. The spreading of *P. strictum* was not sufficient to provide protection to *Sphagnum* diaspores.

Effect of phosphorus amendment

Fertilization had a significant impact on *Sphagnum* reimplantation. A greater number ($p = 0.003$, Table 2) and percent cover ($p = 0.005$, Table 2) of *Sphagnum* capitula were observed in the fertilized plots than in the controls (Fig. 4). Capitula were noticeably greener[2] and larger in the fertilized plots. It is difficult from our experiment to suggest a fertilization regime. We cannot discriminate if the better

[2] In general, we have noticed from several experiments done in our research group that the regenerating *Sphagnum* tends to be greener than in natural conditions in their first years.

Fig. 3. Establishment of reintroduced companion plant species in combination to naturally recolonizing plants in presence or absence of phosphorus amendment (S, *Sphagnum*; H, herbaceous; M, mosses; C, control; E, ericaceous) after two growing seasons.

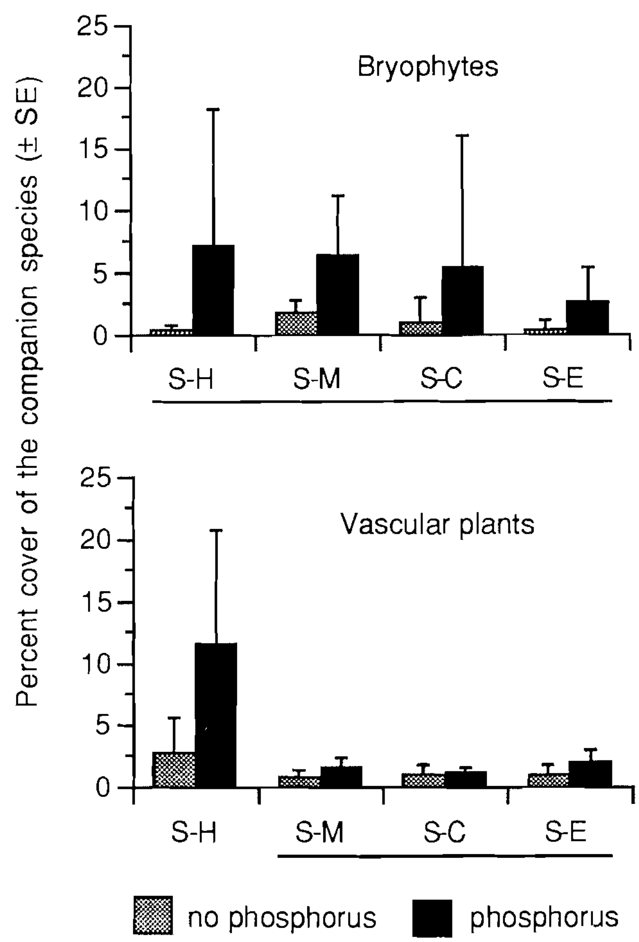
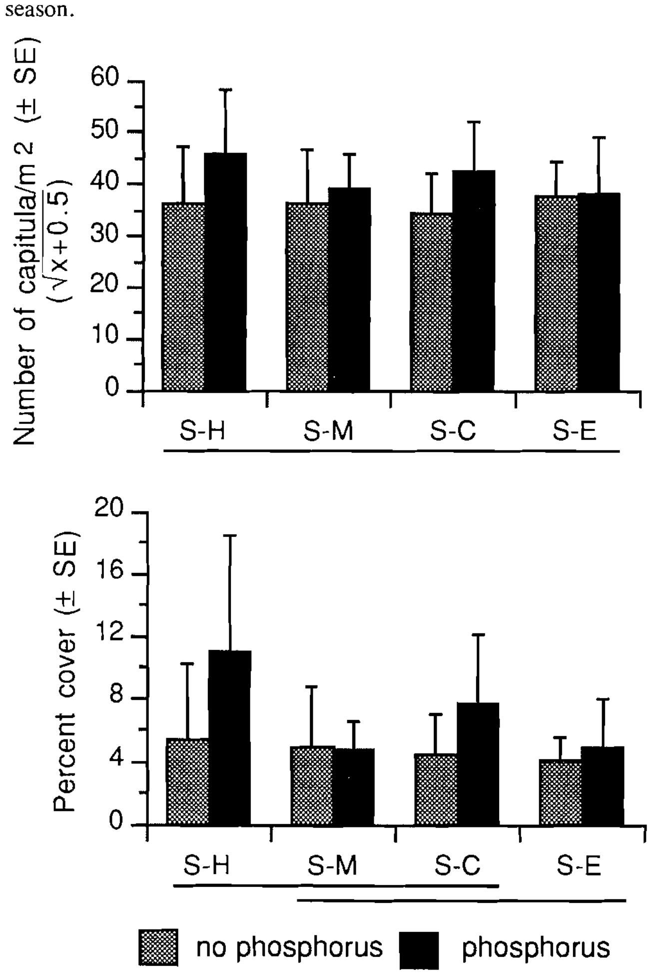


Table 3. Analyses of variance of the percent cover by total vascular plants and bryophytes after two growing seasons.

		Vascular plants		Bryophytes	
Source of variation	df	Mean square	*p*	Mean square	*p*
Main plots					
Microrelief (M)	1	38.7	0.261	1.1	0.911
Error a	4	22.6		77.0	
Subplots					
Companion species (C)	3	107.6	0.003	16.7	0.557
M × C	3	21.9	0.225	61.1	0.097
Error b	12	13.1		23.1	
Sub-subplots					
Amendments (A)	1	88.8	0.0002	244.4	0.006
M × A	1	19.1	0.042	11.2	0.512
C × A	3	51.2	0.0001	11.9	0.703
M × C × A	3	13.1	0.046	48.3	0.164
Error c	16	3.9		24.9	

Fig. 4. Effect of companion plant species (S, *Sphagnum*; H, herbaceous; M, mosses; C, control; E, ericaceous) and phosphorus amendment on *Sphagnum* establishment. Plant communities underlined together show no significant differences in the number of *Sphagnum* capitula observed after one growing season.



establishment of *Spagnum* is due only to light fertilization of the second year or the residual effect of the heavier phosphorus fertilization of the first year. The interaction between companion plant community and amendment was nearly significant ($p = 0.056$, Table 2) for *Sphagnum* cover, which shows the positive effect of the combination of a well-established herbaceous cover and phosphorus fertilization. The best recolonization success of diaspores was observed when they were reintroduced on the *E. angustifolium* fertilized plots. Figure 3 shows that these plots had the highest vascular plant cover, and thus would offer the greatest protection to the diaspores. The fertilized *Eriophorum* plots were also the only plots where the number of capitula and the percent cover (Fig. 5) of *Sphagnum* were similar between ridges and depressions.

Phosphorus addition of the first year also had a significant influence on total vascular plants and companion mosses cover ($p = 0.0002$ and 0.006, Table 3). Establishment success was always higher on fertilized plots (Fig. 3). The results presented in Fig. 3 include both reintroduced plants and those naturally recolonizing. Numerous seedlings of ericaceous shrubs, coming from the transplants that flowered, were also observed in the fertilized plots in comparison with the control where they were far less numerous.

Hydrological and chemical conditions of the experimental substratum

Exploitation activities influence the water chemistry of the ombrotrophic peatlands (Table 1). The pH values of the abandoned site were similar to those of the natural site. Conductivity values are higher on the experimental site but are, in general, in the range of those occurring in naturally acidic bog waters, which are usually under 60 μS (Vitt et al. 1995). Results also show an enrichment of the cations Ca, Mg, K, and Na and of Cl, SO_4, and NO_3-N in comparison with the natural site. In general, phosphorus concentrations remained low, similar to values found in natural peatlands. Ammonium is the nutrient that has increased the most from

Fig. 5. *Sphagnum* establishment after one growing season of unfertilized (−P) and fertilized (+P) plots with microrelief for each companion species community (S, *Sphagnum*; H, herbaceous; M, mosses; C, control; E, ericaceous).

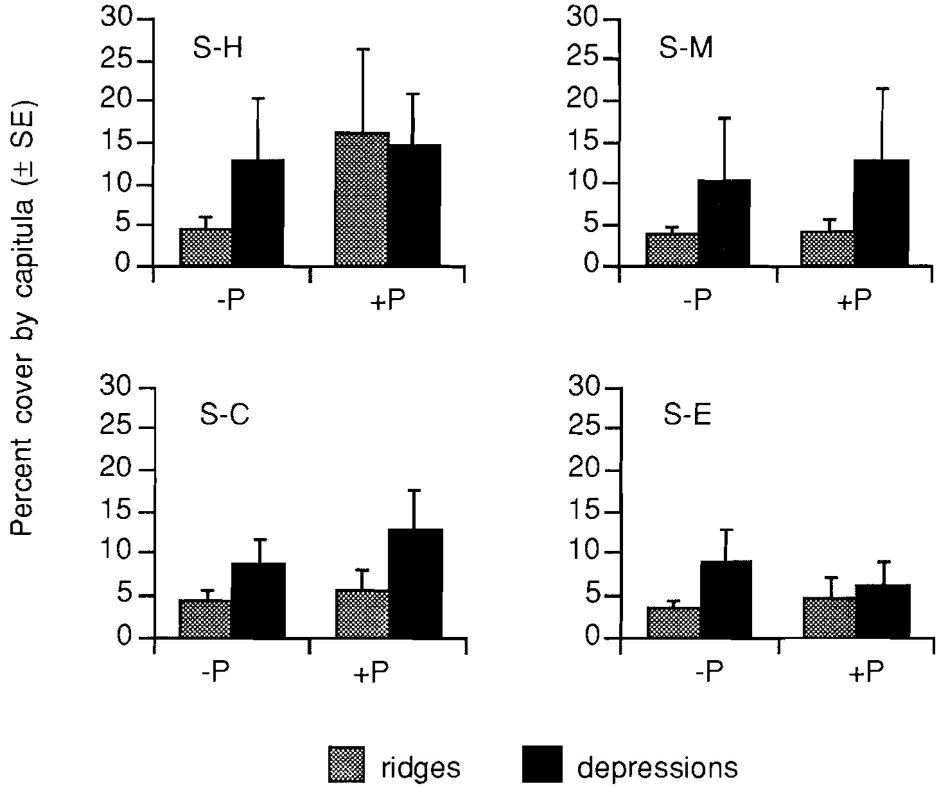
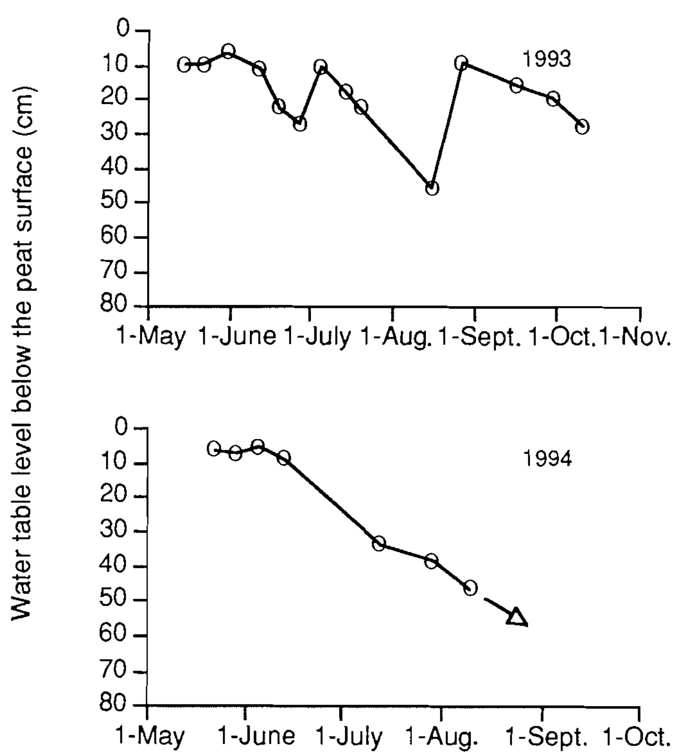


Fig. 6. Water table fluctuations in 1993 and 1994 at the restoration site (n = 35) at Maisonnette. The open-headed arrow indicates that the water table was located lower than −45 cm from the peat surface (maximum depth of many wells).



natural conditions (<0.5 mg/L in the natural site in comparison with a maximum of 16 mg/L in the experimental site). These water chemistry results show that chemical conditions changed with human activities and are now closer to poor fen conditions with an enrichment of nutrients.

Hydrological conditions at the experimental site are illustrated in Fig. 6. Abundant rain in summer 1993 maintained the water table at a relatively high level. From May to mid-July, the water table remained within 20 cm of the peat surface. Very dry conditions in the summer of 1994 caused a marked drop of water levels to under 45 cm from the peat surface.

Discussion

Topographical and hydrological considerations in *Sphagnum* establishment

Results of the effect of varied microrelief suggest a better recovery of *Sphagnum* in the depressions, which are probably less exposed to wind and desiccation than the ridges or flat surfaces (Fig. 2). In this experiment, the ridges were the same width as the depressions. Hence, a microrelief created to form ridges narrower than depressions would increase the area that could be effectively colonized by Sphagna. At the beginning of the restoration process, Sphagna would be more protected in depressions to rapidly form a carpet. The *Sphagnum* species that readily form hummocks could later colonize the artificial ridges created by the plough through the process of paludification. Thus, we assume that increasing surface roughness to create humid, protected microhabitats will help to enhance Sphagna establishment.

It is recognized that the primary important step in peatland restoration consists in rewetting abandoned sites to provide appropriate moisture levels for vegetation of humid environments (Wheeler and Shaw 1995). Blocking the main ditches was successful at rewetting the experimental site with the abundant spring rain and snowmelt characteristic of this climatic region. The experimental section was lower than the surrounding harvested peatland, thus it also tended to collect runoff and drainage water from neighboring areas. However, measurement of water levels during the 2 years of experimentation shows that blocking of ditches alone cannot ensure a stable water table near the peat surface for the entire growing season. Fluctuations of the water table are also more important in harvested peat fields than in natural peatlands (Price 1996). Schouwenaars (1988) stated that water level fluctuations to more than 40 cm below the peat surface are too great to support the establishment of *Sphagnum*. Our results show that *Sphagnum* diaspores survived even though the water table dropped below 40 cm for 48% of the time between May and September 1994; however, the regeneration capacity of the diaspores was affected. Mosses tend to enter dormancy when there is insufficient moisture (Chopra and Kumra 1989). Observations in the course of the two summers suggest that the surface tends to dry rapidly, even when the water table is near the surface. *Sphagnum* diaspores can only access humidity that is present at the peat surface, and wind and sun cause dessication of this surface. Unpublished data from our research group suggest that even when a water table is maintained artificially near the surface, *Sphagnum* mosses show better establishment when provided with a protective cover (mulch or screen shade) than without protection. Restoration of hydrological conditions is still of prime importance to prevent further decomposition of the peat substrate; however, a supplementary protection in the form of companion species or artificial covers would ensure better conditions for *Sphagnum* reimplantation. In other words, supply of water to the *Sphagnum* diaspores via groundwater is not enough and it appears paramount to improve humidity conditions at the peat–air interface.

Effect of companion plant species on *Sphagnum* establishment

Good establishment of *Sphagnum* diaspores was obtained under a cover of *E. angustifolium*, which, of all companion species tested, was the most successful in facilitating the bare substrate recolonization. The association *Sphagnum* – *E. angustifolium* was also described as advantageous by Joosten (1992), who observed a great expansion of *Sphagnum cuspidatum* and *S. recurvum* following the natural implantation of cotton grass. Another interesting fact is that an equivalent number of capitula was counted on ridges and depressions in fertilized plots of *E. angustifolium* in comparison with all other plots where the number of capitula was less numerous on ridges. Even if the ridges seem to be microhabitats less appropriate than depressions for the reimplantation of *Sphagnum*, this microrelief effect was likely balanced by the presence of a well-established plant cover. Our results are consistent with those of Grosvernier et al. (1995), who stated that vascular plants are an effective alternative to create a favorable microclimate in conditions of otherwise unsuitably low humidity of the bare substratum.

The recolonization success of companion species introduced in summer 1993 was variable. After the first growing season, the ericaceous shrubs had survived the transplantation well, but in spring 1994 plants were adversely affected (percent cover <5%). The recovery of rhizomes before winter was probably not advanced, so the plants were sensitive to frost. Ericaceous shrubs were collected from a natural bog and separated individually, which necessitated some breaking of rhizomes. The collection and transplantation of a group of plants would have probably diminished transplantation shock. Also, some plots were inundated in spring, which probably affected shrub survival. As a consequence, ericaceous shrubs did not effectively protect *Sphagnum* diaspores. For future trials, or in a view of large-scale restoration, preliminary multiplication of cuttings in a greenhouse could prove a better approach. Establishment of seedlings instead of mature plants would be easier and would also avoid disturbance of natural peatlands. On the other hand, *Eriophorum* showed a clear propagation success from the first growing season (Fig. 3). This species propagates better in wet conditions, whereas plants multiplied more slowly in dry conditions. Richards et al. (1995) have mentioned that *E. angustifolium* is a species of great value for revegetation of abandoned peatlands by reason of its ecological amplitude and its rapid propagation. Forbes (1993) also observed good natural revegetation of *E. angustifolium* in disturbed high arctic sedge–moss meadows. In our experiment, *E. angustifolium* enhanced *Sphagnum* establishment by their effect on microclimate, i.e., by keeping more moisture at the peat–air interface of the substratum and by providing shade. Cotton grass can also help stabilize the substratum with their interlacing rhizomes. Although companion mosses had begun to establish (percent cover <10%), it is still too early to know to what extent they could favor *Sphagnum* establishment. We expect, however, that with a greater covering they will help to maintain a moist substratum.

Despite variable degrees of establishment success of the different species, the use of companion species remains promising. Moreover, the reintroduction of vascular plants in association with *Sphagnum* increases plant diversity of the system to be restored.

Chemical considerations for *Sphagnum* establishment

Independently to companion species cover, phosphorus application favored a better establishment of *Sphagnum* diaspores in terms of higher number and percent cover of capitula. Money (1995) observed the same trend, i.e., increased growth following phosphorus fertilization for two *Sphagnum* species introduced in pools.

Vascular plants, especially *E. angustifolium*, and companion mosses also took advantage of the phosphorus amendments. *Eriophorum* cyperoids are known to benefit from an increased nutrient supply (Tamm 1954; Damman 1987). This was clearly shown by the higher percent cover observed on fertilized plots. On plots where ericaceous shrubs were reintroduced along with phosphorus amendment, we noticed the presence of numerous ericaceous seedlings, which seem to be stimulated by the addition of phosphorus. The seedling stages are often more sensitive to nutrient deficiency than later stages, and phosphorus could help seedlings develop more rapidly (Bradshaw 1987; Gros 1974). Fertilization could act on the establishment of vascular plants, which in turn could indirectly ameliorate *Sphagnum* survival by their effect on microclimate. Appropriately low doses of phosphorus amendments must be calculated so as not to favor appearance of nontypical peatland species, particularly to avoid propagation of weeds if adjacent peat fields are still being harvested.

Harvesting methods cause radical physical modifications to peatland environments. This can lead to significant departures from initial chemical conditions that result, for example, from alterations of hydrology, aeration of the peat deposit, removal of living vegetation, and exposure of peat formed in earlier developmental stages. Chemical conditions of the abandoned site are now closer to those of a poor fen. This was not considered a barrier for trying to reintroduce *Sphagnum*-dominated vegetation, as it is known that few plants are found exclusively in bogs and many *Sphagnum* species occupy poor fens. Wheeler (1988) suggested that ombrotrophic chemical conditions are not an essential prerequisite for bog plant establishment. Our results support these observations, since most introduced plants, i.e., *Sphagnum*, vascular plants, and brown mosses commonly found in bogs, established themselves on the slightly nutrient and mineral enriched substrata.

Sphagnum diaspores must face far greater limiting factors to their reestablishment on abandoned peatland than simply the availability of nutrients. Fertilization could be seen, however, as a complementary approach to facilitate and accelerate plant establishment once humidity levels have been corrected. At the Maisonnette site, phosphorus was generally not much influenced by harvesting and remained as low as in natural sites, where this element is already considered limiting. In this experiment, all plants benefited from phosphorus amendment.

Conclusions

The establishment of *Sphagnum* diaspores taken from a natural peatland and reintroduced on bare peat surfaces proved successful. This restoration approach, in combination with techniques aimed to improve moisture conditions of the substrata, including the creation of a varied microrelief and the use of companion species, has facilitated reimplantation of *Sphagnum*.

Creation of a microrelief consisting of a series of depressions and ridges favors an improved regeneration of Sphagna in the depressions compared to flat surfaces and ridges. Consequently, it would appear appropriate to create a microrelief that would minimize the width of ridges where *Sphagnum* establishment tends to be very poor.

A good establishment of vascular plants, for example *E. angustifolium* in this experiment, gave a better protection to *Sphagnum* diaspores in comparison to the control, which lacked any cover. Companion plant species provide a good protection and ameliorate unfavorable microclimatic conditions at the barren peat surface. Steps to improve vascular plant establishment will, in turn, also improve *Sphagnum* implantation.

The application of phosphorus amendment also favors *Sphagnum* reimplantation, increasing establishment of *Sphagnum* directly and indirectly by increasing establishment of companion plant species in our experiments. Higher levels of phosphorus fertilizers than those applied in the second year would allow a better establishment of vascular plants but would be detrimental to bryophytes. For optimal results, vascular plants should be reintroduced on a fertilized substratum, and then *Sphagnum* diaspores can be reintroduced once the levels of nutrients have been allowed to drop. Few experiments have been conducted in the field on *Sphagnum* fertilization, and further work is needed to determine appropriate dosages, mode of application, and long-term effects of this technique.

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