Wetlands Ecology and Management **11:** 3–20, 2003.

North American approach to the restoration of *Sphagnum* dominated peatlands

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Received 16 March 2001; accepted in revised form 5 June 2002

Key words: bog, ecological engineering, mire, peat moss, rehabilitation, revegetation, technique

Abstract

Sphagnum dominated peatlands do not rehabilitate well after being cutover (mined) for peat and some action needs to be taken in order to restore these sites within a human generation. Peatland restoration is recent and has seen significant advances in the 1990s. A new approach addressing the North American context has been developed and is presented in this paper. The short-term goal of this approach is to establish a plant cover composed of peat bog species and to restore a water regime characteristic of peatland ecosystems. The long-term objective is to return the cutover areas to functional peat accumulating ecosystems. The approach developed for peatland restoration in North America involves the following steps: 1) field preparation, 2) diaspore collection, 3) diaspore introduction, 4) diaspore protection, and 5) fertilization. Field preparation aims at providing suitable hydrological conditions for diaspores through creation of microtopography and water retention basins, re-shaping cutover fields and blocking ditches. It is site specific because it depends largely on local conditions. The second step is the collection of the top 10 centimetres of the living vegetation in a natural bog as a source of diaspores. It is recommended to use a ratio of surface collected to surface restored between 1: 10 and 1: 15 in order to minimize the impact on natural bogs and to insure rapid plant establishment in less than four years. Diaspores are then spread as a thin layer on the bare peat surfaces to be restored. It has been demonstrated that too scant or too thick a layer decreases plant establishment success. Diaspores are then covered by a straw mulch applied at a rate of 3 000 kg ha^{-1} which provides improved water availability and temperature conditions. Finally, phosphorus fertilization favours more rapid substrate colonization by vascular plants, which have been shown to help stabilize the bare peat surface and act as nurse plants to the *Sphagnum* mosses.

Introduction

Peatland restoration is a relatively new field of investigation that has been the object of significant advances in the 1990s. The European and North American approaches to peatland restoration have differed greatly so far (Money and Wheeler, 1999) mostly because of different land uses of peatlands, peat mining methods, and goals for restoring regional biodiversity. This paper is concerned with the restoration of *Sphagnum* dominated peatlands for sites in North America where peat has been extracted extensively by vacuum harvesting methods (Crum, 1988) or by mechanical block cutting methods. The focus of the approach is to successfully establish a *Sphagnum* carpet (Rochefort, 2000), as *Sphagnum* species are the great engineers of peatland formation (van Breemen, 1995).

Given that little natural regeneration of *Sphagnum* mats occurs on peat fields that have been extracted by vacuum methods (Lavoie et al., this issue), active management appears necessary to speed up recovery. In Canada, some peatlands are not recolonised by *Sphagna* even after 30 years of natural succession (Desrochers et al., 1998). As peatland ecosystems in southern Canada are relatively less abundant than in the boreal zone (NWWG, 1988) and this is the zone where most human activities on peatlands takes place, the long term objective in peatland after-use is often the return to a functional peat accumulating ecosystem (Rochefort, 2000). The return to a functioning peatland within 20 to 30 years would be quite acceptable, but we do not know yet if this is realistic. However, the short term objectives are to establish plant cover composed of peat bog species (3 to 5 years) with particular attention to *Sphagnum,* and to recreate hydrological conditions similar to natural bogs.

The North American peatland restoration method consists of the following steps: 1) field preparation, 2) diaspore collection, 3) introduction and protection, and 4) fertilization. Diaspores are any part of a plant that can regenerate a new individual; such as seeds, rhizomes, shoots or branches.

The first step, field preparation aims at providing suitable hydrologic conditions for diaspore survival. It has been discussed at length in other papers and will not be part of experiments presented in this study. The last step for peatland restoration, fertilization is the subject of a future publication. Nevertheless, a short review of these two steps will be presented in the discussion to complete the overall North American approach to the restoration of peatlands.

This paper presents results from experiments which assessed 1) the regeneration potential of diaspores collected in undisturbed bogs, 2) the effect of mechanized operations (collecting and spreading) on diaspore viability, and 3) ways to improve diaspore establishment success.

Material and methods

Plant collection and regeneration potential of Sphagnum

1. Diaspore collection depth

The objective of this field experiment conducted at Sainte-Marguerite-Marie peatland, Lac-Saint-Jean (48°47′N, 72°10′W; Figure 1) was to assess the depth at which viable *Sphagnum* diaspores can be obtained within the peat column. Detailed description of this field experiment is presented in Campeau and Rochefort (1996). In summary, twelve peat cores (17 cm diameter, 30 cm long) were collected in monospecific patches of *Sphagnum angustifolium, S. magellanicum* and S. *fuscum* (four cores per species). Each core was cut into three sections (0–10, 10–20 and 20–30 cm measured from the peat surface). Material from each layer and core was reintroduced in a 1 m^2 plot located on a bare cutover peat surface at the beginning of June 1993. Plots were grouped in four blocks of three plots, i.e. with one plot (core) per species per block. The experimental site had been rewetted the previous year. Control plots with no material reintroduced were also prepared. All plots were covered with a plastic shade cloth (Agrinet, 40% shade, Les Industries Harnois Inc., Joliette, Québec, Canada). In fall 1993, 1994 and 1995, the number of capitula was counted for 4 quadrats (25 $\times$ 25 cm) within each 1 m^2 plot. Statistical analyses were run according to a split-split plot analysis of variance in a randomized complete block design with species (cores) as a main factor, layer within peat core as the split factor and time (year of measurement) as the split-split factor. To account for the repetitive nature of the time factor, a Box correction was applied to degrees of freedom for all tests involving the factor time or the interactions between time and other factors (Milliken and Johnson, 1989). Data were square-root transformed prior to analysis to reduce heterogeneity of variances. All analyses were performed using the GLM procedure of SAS (Statistical System sofware, v. 6.12, SAS Institute Inc.).

2. Regeneration of Sphagnum *fragments according to distance from capitula*

Building upon the findings of the previous experiment, the design of this growth chamber study aimed at defining in more detail the depth at which *Sphagnum* fragments from different species can no longer be used to regenerate new colonies. Eight species of *Sphagnum* moss (Table 1) were collected by hand in peatlands of the Lac-Saint-Jean region, Québec, (48°47′N, 72°10′W; Figure 1) in the fall of 1993. Individuals were approximately 10 cm long, with the exception of *S. riparium* stems, which were up to 22 cm long. Bundles of stems with capitula were placed in plastic bags and were kept frozen at –2 °C from the day of collection to the onset of the experiment in January 1994.

Twenty individuals per species were used in each of the three replicates of this experiment. The 20 individuals were cut in 1 cm long segments starting from just below the capitula. All 20 segments from the same depth, species and replicate were placed

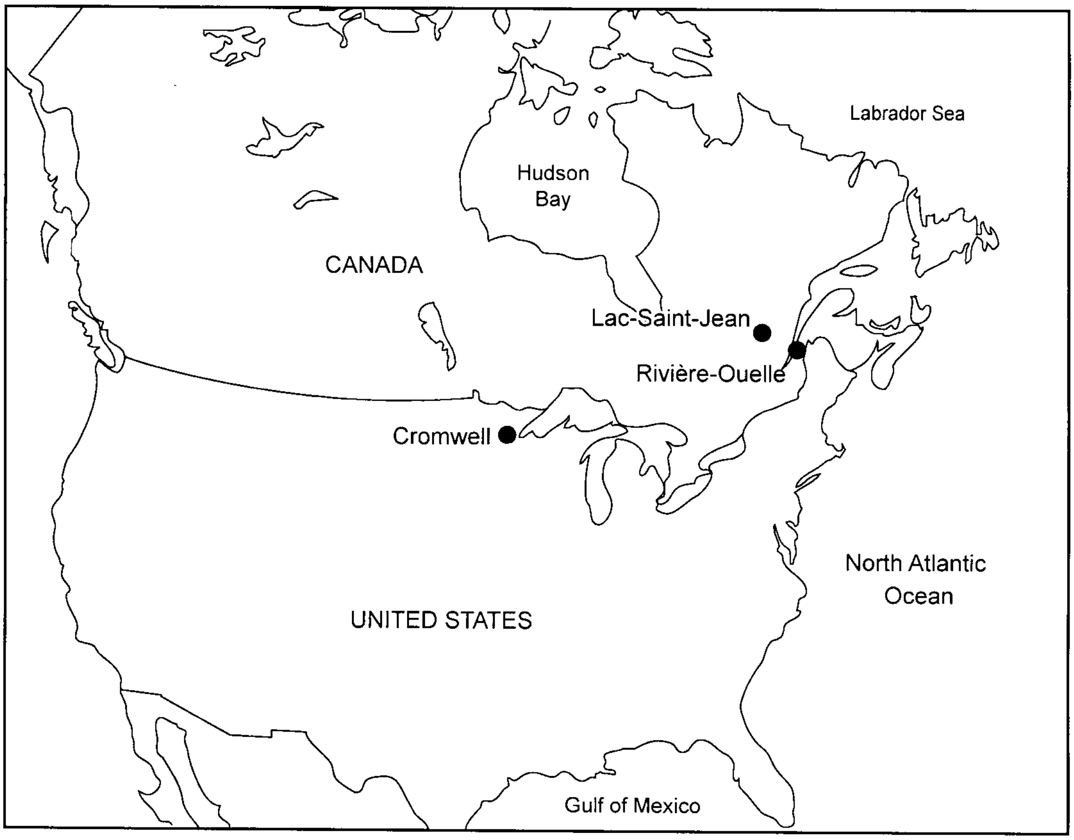

Figure 1. Location of study sites in North America.

in a covered Petri dish fitted with a Whatman filter paper. Fragments were wetted using 5 ml of a modified Rudolph et al. (1988) nutritive solution (Campeau and Rochefort, 1996). All petri dishes were randomly placed in a growth chamber under artificial lighting. Photoperiod was set at 14 hours of daylight, and temperature at about 20 °C. A nutritive solution (1 ml) was added to each petri dish once a week. Between those weekly waterings, petris dishes were checked regularly and a few ml of extradistilled water were added to prevent drying out if necessary. Petri dishes were observed once a week for signs of new growth. Every time a newly formed regeneration bud was observed on a plant segment, this segment was recorded as viable (able to regenerate a new individual) and removed from the dish. At the end of the 10 week experimental period, the number of viable fragments was totalled for each petri dish and reported as a percentage of the number of fragments initially used.

Plant introduction

3. Effect of size and density of Sphagnum *fragments*

In this field experiment, we assessed how size and density of *Sphagnum* diaspores affect their establishment on bare peat substrate. We also evaluated how the ability to recolonise bare peat surfaces varies between *Sphagnum* species. Detailed description of this field experiment is presented in Campeau and Rochefort (1996). In summary, this experiment compared the establishment success between two diaspore sizes (1 versus 2 cm long fragments of *Sphagnum* plants), four densities (0, 150, 300 and 450 fragments reintroduced per m^2), and five types of diaspores (*S. magellanicum, S. angustifolium, S. fuscum, S. capillifolium* and a mixture of all four species together) over a three year period. The study took place on a section of cutover peatland where the drainage of 25 adjacents peat fields had been blocked the previous season. The peatland is located in the Lac-Saint-Jean region in

Québec (48°47′N, 72°10′W; Figure 1). Plant reintroduction was done by hand in early June 1993. All plots were immediately covered with a 40% shade screen (Agrinet™). In the fall of 1993, 1994 and 1995, the number of capitula present was counted in 4 quadrats (25 cm × 25 cm) within each plot. The percentage of the peat surface covered by live *Sphagnum* was also estimated visually.

This field experiment was conducted in a split-split-plot randomized complete block design, with 'species' as the main factor (one main-plot unit per species for each of the four blocks), diaspore size and density as the split-factor and time (year of measurement) as the split-split factor. The experiment comprised four blocks. To account for the repetitive nature of the time factor, a Box correction was applied to degrees of freedom for all tests involving the factor time or the interactions between time and other factors (Milliken and Johnson, 1989). Data were square-root transformed ($\sqrt{(x+0.5)}$) prior to analysis to reduce heterogeneity of variances. Analyses were performed using the GLM procedure of SAS (SAS Institute Inc.) The level of significance for testing treatment effects and for multiple comparisons between treatment means was set at 0.05.

While this experiment recorded reintroduction density as the number of plants per square meter, most experimental work conducted by our team after 1994 reported density as the ratio between the collected surface (natural area) to the restored surface. In order to be able to compare results from this experiment to future experiments (e.g. experiment 4, this paper), a series of surface cores (10 cm diameter for *S. fuscum* and *S. capillifolium*, 15 cm diameter for the two other species) were taken during the summer of 1994. Total number of capitula was recorded for each sample, and the average density of *Sphagnum* plants in our collection areas calculated for each species.

4. Effect of Sphagnum *fragment density, shredding, and season of introduction*

This field experiment aimed at improving the efficiency of reintroducing *Sphagnum* fragments. The experiment was carried out in the field at the Sainte-Marguerite-Marie peatland in the Lac-Saint-Jean region, Québec (48°47′N, 72°10′W; Figure 1). A portion of the peatland had been drained and peat had been block-cut to a depth of 40 cm to 60 cm. In the year following peat cutting operations, the drainage ditches of the experimental area were blocked with peat dams. In the fall of 1993, the peat surface on which the experiment would be carried out was thoroughly harrowed to level former relief elements (peat blocks, machinery ruts) and to remove the hydrophobic crust that sometimes forms after peat cutting activities stop.

Twelve plots of 10 × 12 m were delimited on one of the cutover peat fields. Six of these plots were randomly selected and hand sown with *Sphagnum* diaspores in the fall of 1993. *Sphagnum* reintroduction on the other six plots took place in spring 1994.

Sphagnum plants used as diaspores in this experiment were collected by hand from nearby natural peatland areas. The selected monospecific stands of the targeted species (*Sphagnum fuscum, S. capillifolium* (sensu lato), *S. magellanicum* and *S. angustifolium*) had to be large enough to accommodate a 1 m^2 quadrat. The top portion (∼10 cm) of *Sphagnum* was collected by hand over the entire surface of the quadrat. *Sphagnum* diaspores were hand-sown in the experimental plots within a few days of collection. Although manual collection of plant material mainly targets *Sphagnum* plants, numerous seeds, rhizomes, seedlings and spores of other peatland species end up in the collected material. The results for these other bog species will also be presented.

Reintroduction densities were standardized based on ratios between surfaces of collected areas and surfaces of restored areas (Campeau and Rochefort, 1996). Mixtures of diaspores were spread either at a 1: 10, 1: 20 or 1: 30 density ratio (2 plots per density for each reintroduction period). For example, the 1: 10 ratio translated in the field to 3 m^2 of *S. capillifolium,* 3 m^2 of *S. fuscum,* 3 m^2 of *S. magellanicum* and 3 m^2 of *S. angustifolium* being mixed together and spread over one 120 m^2 plot. In one out of the two plots per species per reintroduction period, the hand-collected diaspores were cut in small pieces mechanically using a straw shredder (hereafter referred to as 'shredded'). The resulting fragments were often small (0.25 cm to 2 cm), and the plants often seemed more crushed than shredded. The other plots received unshredded *Sphagnum* plants (with stems between 5 and 10 cm long).

In the spring of 1994, both spring and fall experimental plots were covered with a protective layer of straw mulch (Price et al., 1998). In order to ensure a dense straw cover throughout the establishment phase, a second, lower density, mulch application was done in the spring of 1996.

Plant establishment was monitored each fall from 1995 to 1997 and in 1999 by visually estimating the percent cover of *Sphagnum* mosses, as well as other mosses and vascular plants on series of 25 × 25 cm quadrats. Quadrats were located systematically along transects running across the plots (Brakenhielm and Qinghong, 1995). The number of quadrats sampled in each plot every year varied from 28 to 36.

Analyses of variances were performed using the GLM procedure of SAS (SAS Institute Inc.) using a split-plot design with season, density and type of diaspores as main factors and time (year of measurement) as the split factor. As there was no true replication of each combination of treatment (2 seasons × 3 densities × 2 types of diaspores), the three way interaction (season*density*type) was used as the error term for testing main factors effects and their interactions. To account for the repetitive nature of the time factor, a Box correction was applied to degrees of freedom for all tests involving the factor time or the interactions between time and other factors (Milliken and Johnson, 1989). Data were log transformed prior to analysis to reduce heterogeneity of variances. The level of significance for testing treatment effects and for multiple comparisons between treatment means was set at 0.05.

5. Thickness of introduced plant material

This experiment tested the influence of many factors such as windbreaks, cover, topography and plant thickness on vegetation establishment on bare peat. Attention will be given here to the thickness of plant material reintroduced. Some results (1993) for this experiment have already been published, and methods are fully described in Quinty and Rochefort (1997) and Rochefort et al. (1997). The study site is a 15 km^2 peat bog located at Rivière-Ouelle (47°27′N, 69°58′W; Figure 1). The drainage ditches were blocked in 1993. The original experiment aimed at assessing the effect of various covers on plant establishment. To do so, plant material was spread mechanically over a large area, on which a series of plots with mulch (1500 kg ha^{-1}), plastic covers and no-cover were established. Mechanical spreading operations of diaspores resulted in strips of material with different densities, which superposed themselves across the original experimental plots. These“sub-plots” were qualified as the 1) no plant, 2) scant layer, 3) thin layer (1 cm) and 4) thick layer (more than 2 cm). Percent cover by *Sphagnum,* other mosses and vascular species was assessed yearly in 25 × 25 cm quadrats in 1994, 1995 and 1996.

Plant protection

6. Comparison of the effect of different covers on plant establishment

This experiment aimed at testing different types of protecting cover readily available in the region. Living plant material was collected mechanically with the aid of a rototiller, shredding the top surface (5 to 10 cm depth) of the moss layer in an untouched part of a bog in Rivière-Ouelle (47°27′N, 69°58′W; Figure 1) in the spring of 1994. A manure spreader was used to disseminate the living plant fragments on the experimental site to a surface 10 times larger than the undisturbed site (ratio collected-surface to surface-covered 1: 10). Three plots (6 × 6 m) were delimited on the bare peat surface of the experimental site. Each plot was subdivided in 4 plots (3 × 3 m) that received the four cover treatments: no cover, straw, shade screen and by-product roots from the sieving of the commercial peat. The straw was applied at a density corresponding to 1 500 kg ha^{-1}. We used a 57% shade screen (Agrinet 57%™) and stapled it to a wooden frame to maintain it in place. As the roots came from the screening of the commercial peat, they probably came from ericaceous shrubs. They were applied in a way to cover about 20% of the ground surface.

Vegetation establishment was assessed by estimating the percent cover of *Sphagnum* mosses, other mosses, herbaceous plants and ericaceous shrubs from a series of 25 × 25 cm quadrats systematically located within each plot in the fall of 1994, 1995, and 1996.

7. Effect of straw mulch and season of introduction on plant establishment

The experiment was conducted at a site previously vacuum harvested for horticultural peat located east of Cromwell, Minnesota in Carlton County (46°41′N, 92°45′W; Figure 1). The experimental treatments consisted of two mulch treatments (straw mulch, no mulch), two companion species treatments (*Carex oligosperma,* no companion species), and two plant spreading time treatments (fall, spring) for a total of eight treatment combinations. The study was established in a randomized block design, with six replications of each treatment, resulting in a total of 48 plots (1.5 × 1.5 m). The plant material, the top 10 cm layer collected from natural sites adjacent to the study site, was spread on all research plots at a density ratio of 1: 10 (one part collected area to 10 parts restored area).

For the mulch treatment plots, a uniform layer of straw mulch (equivalent to approximately 3 000 kg ha^{-1}) was distributed over the plant material. Each of the above treatments was initiated during fall (October) 1997, and repeated again in spring (May) 1998. Companion species effect is not discussed at length in this paper but for more details on this effect within the Minnesota experiment see Johnson et al. (2000).

Percent cover determinations for all treatments were conducted in October 1998 and 1999 by visually estimating percent cover for four 25 × 25 cm quadrats placed systematically within each study plot. Vegetative cover categories included total plant cover, *Sphagna,* mosses other than *Sphagna* (predominantly *Polytrichum strictum*) and vascular plants. Vascular plants included graminoids and ericaceous shrubs.

Collected data were analyzed according to SAS General Linear Model procedures to determine treatment effects. Where appropriate, data were transformed to comply with statistical assumptions of normality and equal variance. SAS computer software (version 6.12) was used to conduct the analyses. Statistical analysis results for only the 1999 data are reported in this paper.

8. Effect of straw density and the season of mulch application on plant establishment

Because straw mulch can decompose and its structure can change rapidly over time, an experiment was designed to evaluate the effect of fall versus spring mulch applications on plant establishment. Living plant material was collected mechanically with the aid of a rototiller. The top surface (5 to 10 cm depth) of the moss layer was shredded from a pristine area of the bog in Rivière-Ouelle (47°27′N, 69°58′W; Figure 1). A manure spreader was used to spread the living plant fragments on the experimental site to a surface 20 times larger than the undisturbed site (ratio collected-surface: surface-covered 1: 20). The abandoned field was ploughed prior to the spreading of plants in the fall 1993 to create microtopography. The site was divided in plots 10 × 10 m. Straw mulch was applied by hand at determined densities in the fall 1993 and the spring 1994. The fall 1993 application rate was 1 500 kg ha^{-1}. The spring 1994 application rates were 750, 1 500 and 3 000 kg ha^{-1}.

Vegetation establishment was assessed by estimating the percent cover of *Sphagnum* mosses, other mosses, herbaceous plants and ericaceous shrubs from a series of 14 quadrats (25 × 25 cm) systematically located along transects within each plot in the fall of 1994, 1995, and 1996. The water table was monitored weekly during the growing season in two transects of four wells located at both ends of the site.

Results

Plant collection and regeneration potential of Sphagnum

1. Experiment on diaspores collection depth

Results obtained in this experiment after the first field season (1993) are presented in Campeau and Rochefort (1996). Data collected after the second and third field seasons (Figure 2) corroborate our earlier findings. Due to a significant species*depth interaction, the number of capitula recorded had to be compared between depths within each species individually. For all three species tested, the number of capitula observed for plots that received material from the 0–10 cm peat layer was higher than for control plots or plots that received material from lower layers. However, no significant differences between control plots and plots receiving material from the 10–20 cm and 20–30 cm layer were detected. Although the number of capitula observed in each treatment varied with time (the drop observed in 1995 corresponding to a very dry growing season), the three year data set showed no evidence that the early difference in number of capitula between the surface layer and the two lower layers would attenuate in time (no significant time*depth interaction).

2. Regeneration of Sphagnum *fragments according to distance from capitula*

The depth at which fragments of *Sphagnum* plants can regenerate new capitula vary greatly between species (Table 1). For the majority of the species tested, a sharp decline in regeneration potential was observed for fragments originating from a depth of 6 cm under the capitula. However, *S. magellanicum* and *S. papillosum* were still 30% viable up to a length of 10 cm (our experimental limit) and *S. riparium* could regenerate new individuals up to at least 22 cm from the capitula. It is noteworthy that, although differences between species reported here bear some relation to expected species differences in seasonal growth in length, the ‘viable’ part of the plant was not necessarily limited to the portion that had grown in the previous field season. For example, although *S. fuscum* generally grows by 1–3 cm a year (see references in

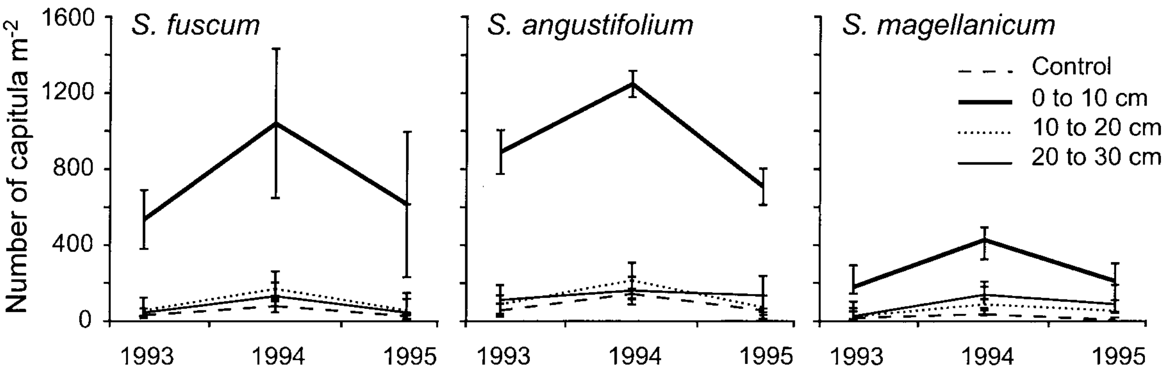

Figure 2. Evolution of the number of *Sphagnum* capitula over two years according to diaspore collection depth for three species (n = 4). Error bars correspond to standard error.

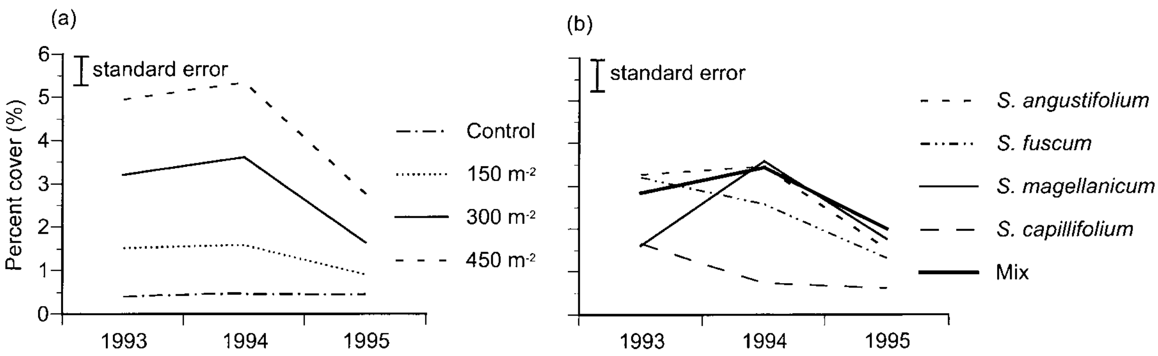

Figure 3. Evolution of cover of *Sphagnum* according to (a) density of reintroduction and (b) species reintroduction. Mix represents a mix of the four species, *S. capillifolium, S. magellanicum, S. fuscum* and *S. angustifolium.*

Rochefort et al., 1990), it can produce new buds from plant segments up to twice that length.

Plant introduction

3. Effect of size and density of Sphagnum *fragments*

For the three years of the experiment there was no significant effect of the size of fragments (1 cm versus 2 cm) on *Sphagnum* reestablishment success, hence, the size was excluded from the final analysis. Density, on the other hand had a significant impact on the number of capitula and *Sphagnum* cover recorded in all years (Figure 3). Although the number of capitula observed in each treatment varied with time with a drop in 1995 corresponding to a very dry growing season, the three year data set showed no evidence of any noticeable development of *Sphagnum* in plots which received no diaspores (significant density*time interactions for cover, Figure 3a). Significant species*time interactions were also observed for capitula counts (Figure 3b) whatever their success in previous years, all species suffered from the dry 1995 season.

The number of diaspores introduced can also be regarded in terms of density of plant material. In order to compare the number of capitula introduced with ratios of surface collected: surface restored used in other experiments, the number of capitula per square meter in natural conditions was determined for six *Sphagnum* species (Table 2). In nature, the number of capitula per square meter is much higher for smaller species such as *S. fuscum* compared to large species like *S. magelllanicum*. Thus, the introduction of 450 *Sphagnum* individuals per m^2 corresponds to ratios of surface collected: surface restored of 1: 100 for *S.*

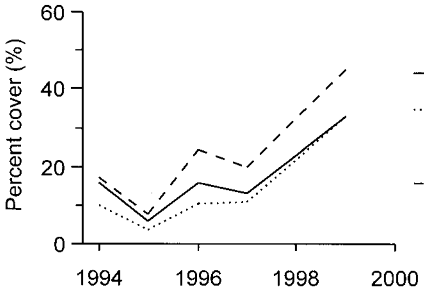

Figure 4. Evolution of percent cover from 1994 to 1999 according to the season of reintroduction and the type of *Sphagnum* diaspore. F and S represent fall and spring respectively.

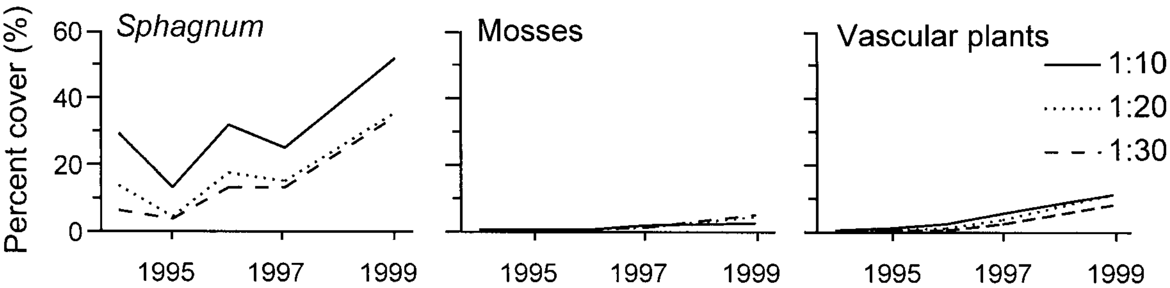

Figure 5. Evolution of percent cover of *Sphagnum,* other mosses and vascular plants from 1994 to 1999 according to the quantity of plant fragments introduced, expressed as ratios of surface collected: surface restored.

fuscum and 1: 40 for *S. magellanicum* and the introduction of 150 *Sphagnum* per m^2 is equivalent to ratios of 1: 340 and 1: 110 respectively for the same species (Campeau and Rochefort, 1996). This is far less than ratios used in other experiments. This also means that the quantity of material introduced was greater for *S. magellanicum* plots than for the other species (in terms of ratio). On the other hand, the number of capitula introduced will be greater for plant material collected in area dominated by small species like *S. fuscum* and *S. capillifolium.*

Differences in number of capitula per surface area likely explain the discrepancies observed between this experiment and experiment number 2 (Figure 2) in term of which species performed best. In one case (this experiment) an equal number of plants were reintroduced for each species, meaning that a smaller surface area of material was reintroduced for *S. fuscum* and *S. capillifolium*, hence their lower establishment rate. In experiment 2, a similar surface area of material was reintroduced for each species. This time, *S. fuscum* and *S. angustifolium* established better than *S. magellanicum,* which is coherent with results of other studies comparing success of different *Sphagnum* species (Chirino and Rochefort, 2000).

4. Effect of Sphagnum *fragment density, size, and season of introduction*

All two-ways interaction terms of the ANOVA with repeated measures were found to be non-significant, hence for clarity, the data are pooled either by season and type of diaspores (Figure 4) or by density (Figure 5). Colonization of bare peat was always slower for mechanically shredded plants than whole *Sphagnum* mosses (Figure 4). Furthermore, plant reintroductions done in the spring were more successful than the ones done in the fall. We can not, however, know if this difference is due to better establishment conditions present in the spring, or to the fact that fall-reintroduced diaspores were only covered with mulch in the next spring, this delay potentially resulting in losses to desiccation. The diminution in the percentage of *Sphagnum* moss cover observed in 1995 reflects the driest summer conditions at this site since our research group has been involved in peatland restoration (1992). Still, the plants were able to recover in 1996, in part due to a very wet summer (July precipitation well above normals).

Clearly, the higher the density of plant material reintroduced, the higher the success of *Sphagnum* moss establishment (Figure 5). With time, differences between the 1: 20 and 1: 30 reintroduction ratios attenuated and became non-significant. Here again, the effects of the dry growing seasons (1995 and 1997) can be observed. However, once a certain level of *Sphagnum* moss establishment is achieved before the occurrence of dry summers, the moss carpet can apparently resume growth in wetter years. Vascular plants were slow to show signs of establishment (Figure 5); it took five years for their percent cover to reach the 5% level. As for *Sphagnum,* establishment success of vascular plants varied significantly between reintroduction densities.

Mosses other than *Sphagnum* were slow to establish and never reached a very important level. Density of reintroduced plant material had no significant impact on other mosses cover (Figure 5). These may be, in part, due to the fact that the vegetation of the donor site had only a very small proportion of mosses other than *Sphagnum.*

5. Thickness of introduced plant material

Data from this experiment taken after one growing season revealed that a thin layer of plant material (1–2 cm) allows for a better plant establishment than a scant or a thick (> 2 cm) layer (Quinty and Rochefort, 1997). After four growing seasons, we observe the same pattern regarding plant material thickness with total plant cover of 17% for scant and thick plant layers and 24% for the thin layer (Figure 6). However the species composition of plant communities evolved differently. Scant and thin layers show similar plant communities with the dominance of mosses (mostly *P. strictum*) that account for about half of the new carpet, with a third of *Sphagnum* and the remaining portion (one-fifth) of vascular species. In the case of a thick plant material layer, the plant community is composed mainly of vascular species. The results of this experiment started in 1993 also confirm the important effect

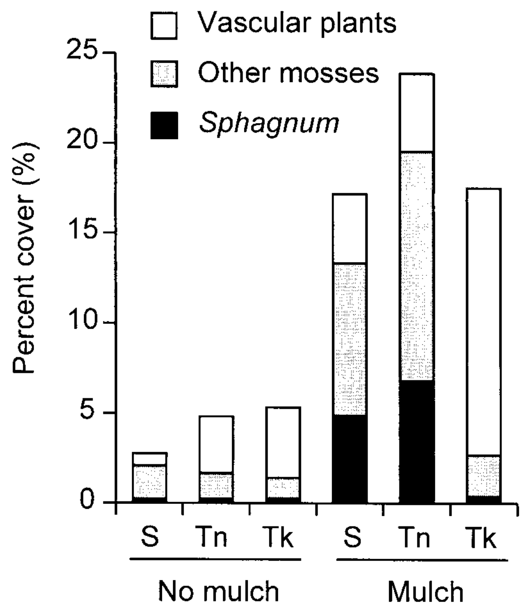

Figure 6. Mean percent cover of *Sphagnum,* mosses, vascular plant and total cover after three years (1996) according to the thickness of plant material spread on bare peat surfaces. S represents a scant layer of plant fragments, Tn a thin layer and Tk a thick layer.

of straw mulch on plant establishment, as the total plant cover was less than 5% without mulch compared to more than 15% with straw mulch. Moreover, plots without mulch are almost totally devoid of *Sphagnum* while they account for up to a quarter of the newly established plant community in mulched plots.

It is noteworthy that this site is very dry. The water table may reach 30 cm below the surface in the spring and its stays far below 40 cm for most of the growing season. The summer of 1995 was especially dry and the water table dropped below 60 cm under ground surface and did not recover to its normal high level by mid-October. Harsh conditions associated with the 1995 summer drought affected most experiments conducted in Québec (Figures 2, 4 and 5) as shown by a decrease in percent cover of newly established plant carpets.

Plant protection

6. Comparison of the effect of different covers on plant establishment

The three types of cover had a positive effect on the establishment of *Sphagnum* and they were significantly different from the absence of cover (Figure 7).

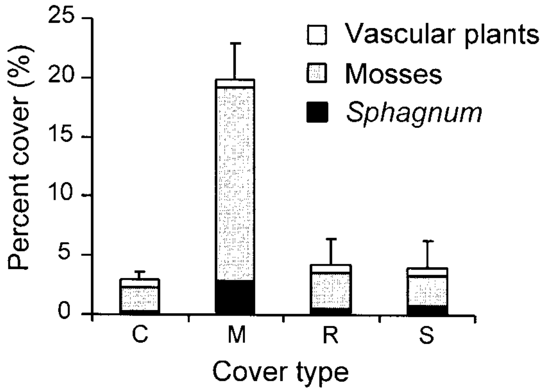

Figure 7. Mean percent cover of *Sphagnum,* mosses, vascular plant and total cover after three years (1996 data presented) according to the type of protecting cover. C represents control plots, M plots covered with straw mulch, R plots covered with roots and S plots covered with shade screen. Error bars correspond to standard error of total cover.

The mosses other than *Sphagna* (mostly *Polytrichum strictum*) composed more than 80% of the plant cover under the mulch treatment. The percent covers obtained under the straw were significantly higher than those under the shade screen (test of Walter-Duncan), while percent covers for the roots and absence of cover were not significantly different. The type of cover did not influence vascular plants establishment.

7. Effect of straw mulch and season of introduction on plant establishment

Conditions at the Minnesota site were probably the most conducive to successful peatland restoration with a mean water table level at 2.1 cm below the peat surface. Mulched plots showed as much as a tenfold increase in total percent cover in the second year, primarily as a result of a dramatic increase in *Sphagnum* cover (Figure 8). The total percent cover for plots with no mulch was not only considerably less than those plots with mulch, but the cover was made up of predominantly vascular plants and other mosses. Statistical analysis of the 1999 percent cover data revealed significant time of reintroduction by mulch interaction effects for *Sphagnum* ($p = 0.003$), other mosses ($p = 0.007$), and total cover ($p = 0.003$). This interaction was similar for each plant category, being that fall mulched plots had greater mean percent cover than spring mulched plots. However, there was no real difference between fall and spring planted plots without mulch. In general, mulched plots had greater percent cover than those without mulch. Therefore, the beneficial effect of fall planting was dependent on mulch application. There was no significant effect of *Carex* on percent cover for any plant category, probably because *Carex* were not given enough time to form a population that could provide some protection.

8. Effect of straw density and the season of mulch application on plant establishment

The comparison of plots where straw was spread in the fall and in the following spring (treatments F1500 and S1500; Figure 9) shows no significant difference after three growing seasons. This means that the plant fragments did not lose their regeneration potential being exposed during the winter months between the two applications of straw. In fact, in this particular experiment, they were never exposed to desiccation due to wet conditions in the fall and spring and because they were covered with snow most of the time. However, from field experience, it helps to spread the straw in the fall, as the abundant fall rain and winter snow prevent it from being blown away.

The major difference between treatments occurs when comparing the quantity of straw used as mulch. The results suggest that plant establishment success increases with higher density of straw mulch (Figure 9). The results do not allow us to determine if 3 000 kg ha^{-1} of straw (often used in practice now) is the optimum quantity as there was no treatment using a larger quantity. It is possible that larger quantities favor better establishment, however, the shading effect of straw could be detrimental to plants at some point.

In this experiment, the water table dropped below 40 cm in late June 1994 and stayed around 50 cm below ground level until October. In 1995, the water table stayed above 40 cm until mid-July but it then dropped to 60 cm and did not recover until we stopped taking measurements in October.

Discussion

Field preparation

In order to harvest peat, peatlands are divided in fields 20 to 40 m wide and of variable length. Fields are separated by drainage ditches about 75 cm deep and 1 m wide that drain water into a main ditch at one end of the fields. Fields are also cambered (convex over long profile) to facilitate the drainage into the ditches. The first step in peatland restoration is the preparation of the fields to stop the drainage and provide wet

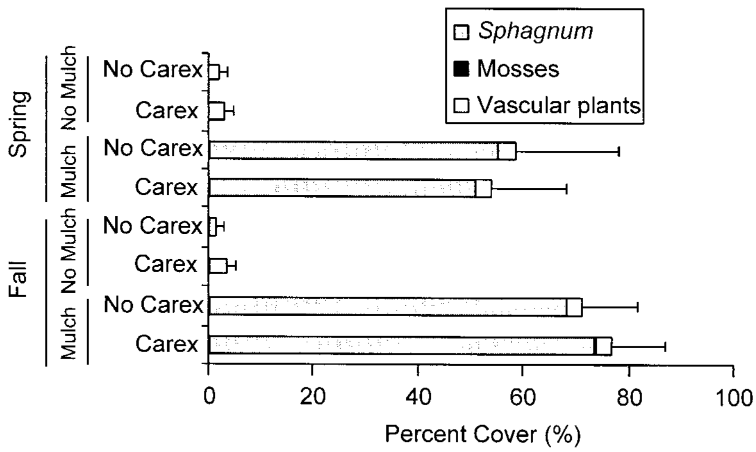

Figure 8. Mean percent cover by *Sphagnum,* mosses and vascular plants after two years (1999) according to the presence/absence of straw mulch, *Carex oligosperma,* and sowing time. Error bars correspond to standard error of total cover.

conditions suitable for the establishment of *Sphagnum* and other plants on the entire surface. In fact, water should be retained as much as possible without extensive flooding. Field preparation varies according to the characteristics of the site and the state of the fields when harvesting stops. Blocking the ditches is an operation that applies to most sites. It seems better to block them after the other operations are completed because the water level can rise rapidly and create unfavourable conditions for machinery work. Completely filling the ditches proved to be an inadequate solution for some sites. Instead, if there is a sufficient water supply, open ditches may play the role of small ponds that help stabilize the water table (Beets, 1992; LaRose et al., 1997) and increase biodiversity (Speight and Blackith, 1983). Reprofiling the fields when they are domed shaped is an important procedure. Bugnon et al. (1997) showed that creating a 'V' shaped profile improved the conditions for the establishment of *Sphagnum* species at the bottom of the slope. However, such a profile leads to the creation of dry conditions in the upper parts of the slope and it may induce runoff and peat erosion causing deposition and burying plant fragments down the slope. Another option that is widely used in Europe for rewetting is the construction of dykes (Wheeler and Shaw, 1995). This method is currently being tested at a site in New Brunswick and preliminary results show that dykes allow significantly higher water level and soil water content, and lower water pressure at the surface compared to the control site (Price et al.,

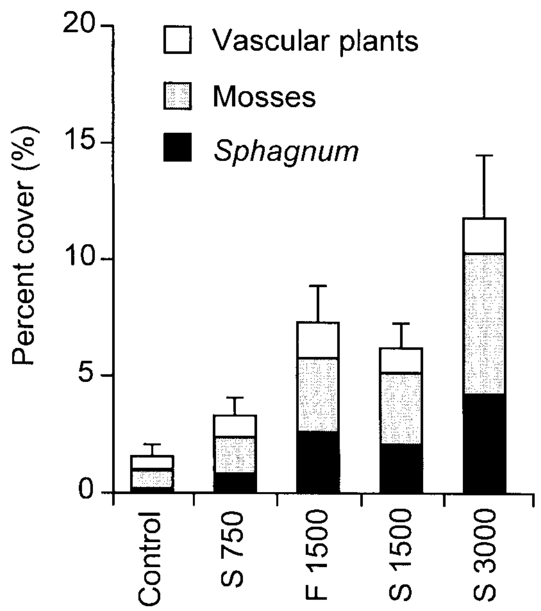

Figure 9. Mean percent cover of *Sphagnum,* mosses, vascular plant and total cover after three years (1996 data presented) by the quantity of straw applied and the season of straw application. S represent spring application of straw and F represents fall application. Numbers refer to kg ha^{-1} of straw, i.e. S1500 means application of 1 500 kg ha^{-1} of straw in the spring. Error bars correspond to standard error of total cover.

this issue). However, dykes protruding above the snow cover freeze deeply and, given the insulating property of peat, they stay frozen for a long period of time in the spring causing surface flooding on unslope areas which can disturb plant fragments (F. Quinty, pers. obs.). In exposed sites in coastal bogs of New Brunswick, dykes also play the role of windbreaks and help keep the straw mulch in place. This option is apparently suitable for sites that have a relatively steep slope but it should be used in combination with overflows in order to avoid extensive flooding. Price et al. (2002) report on the use of shallow basins or trenches based on the natural revegetation of trenches in old block-cut peatlands. Their results showed 20, 10 and 4 m wide basins allow for a rise of the water table by lowering the original surface, retaining meltwater in spring and stormwater in summer and retaining water during dry periods by the groundwater mounds beneath the ridges. In their experiment, basins, as well as straw mulch, decrease the frequency and duration of drought as shown by water tension lower than –25 mb at the peat surface. Spring flooding can occur in the basins and be physiologically advantageous for the regeneration of *Sphagnum* (Rochefort and Campeau, in press). However, extensive flooding can also be detrimental and cause floating of the reintroduced material.

The creation of microtopography was also considered by many authors as a means to provide sheltered sites and nuclei from which bare peat colonization by *Sphagnum* can proceed (Salonen and Laaksonen, 1994). Recent works (Ferland and Rochefort, 1997; Quinty and Rochefort, 1997) tested to a limited extent the effect of depressions on the establishment of plant fragments, but their results were not clear. Quinty and Rochefort (1997) found a positive effect of shallow depressions, whereas Ferland and Rochefort (1997) found no difference between flat, positive, and negative reliefs. Price et al. (1998) conducted a comprehensive study where they measured microclimatic conditions for flat, harrowed, and ploughed surfaces as well as for surfaces composed of tracks and ridges. Their results show that flat surfaces provide the best conditions. The other types of microtopography offer good conditions in sheltered sites (bottom of tracks and furrows), but the overall conditions are not better than that of flat surfaces because of dryness that occurs on areas of positive relief. According to their findings, there was no net gain reshaping the peat surface at the microtopographical in term of environmental conditions for peat moss establishment.

Plant collection

The proposed restoration technique uses plant fragments as diaspores to re-establish a new plant carpet composed of bog species on peat extracted sites. Many studies have shown that fragments of *Sphagnum* moss have the capacity to regenerate new individuals (Clymo and Duckett, 1986; Poschlod and Pfadenhauer, 1989; Rochefort et al., 1995). The easiest way to get enough diaspores is to collect plant fragments in an undisturbed area of a bog. However, it is important to minimize the impact on these sites. Restricting plant collection to the parts that have the best possible potential for regeneration, and restoring as large a surface as possible for a given collected surface represent two ways to minimize this impact. In fact, the most effective ratio of surface collected in natural bog to surface restored in vacuum harvested bog will minimize the donor site area, while ensuring a rapid colonization of surfaces to be restored.

In choosing a donor site, it is essential to make sure that *Sphagnum* species cover a large part of the ground (> 50%). It is also important to consider that different *Sphagnum* species do not have the same regeneration potential (Campeau and Rochefort, 1996; Grosvernier et al., 1997; Chirino and Rochefort, 2000). Fortunately, the most common species in raised bogs of North Eastern America, *S. fuscum, S. capillifolium* and *S. angustifolium* present good regeneration potentials (Table 1 and Figures 2, 3 and 4; see also Campeau and Rochefort, 1996; Rochefort and Bastien, 1998; Chirino and Rochefort, 2000).

Although most parts of *Sphagnum* individuals can regenerate, our investigations showed a rapid decline in the regeneration potential associated with the depth of collection for the most common *Sphagnum* species (Table 1). With the exception of *S. riparium*, which grows in open water, the other species showed poor regeneration potential, if any, for fragments originating below 10 cm. The percentage of regenerating fragments dropped under 50% when collected under 4, 5, and 6 cm from the surface for *S. fuscum, S. capillifolium* and *S. angustifolium*, respectively. In our field experiment, the comparison between fragments collected at 0–10, 10–20, and 20–30 cm revealed clearly that the regeneration potential drops sharply below 10 cm from the surface and that this should be the lower limit when collecting fragments (Figure 2). However, collecting mechanically only the top 5 or 10 cm of the moss carpet in an undisturbed bog is not possible because of the hummock-hollow topography.

In practice, we use a rototiller that will either only chop the top of the hummocks and miss the lower relief elements, or go deeper than 10 cm to make use of the entire collected surface and reach the bottom of the hollows. Ferland and Rochefort (1997) found no difference in the establishment success of fragments collected at 0–10 and 0–20 cm. Nevertheless, field observations suggest that collecting fragments deeper than 10 cm result in a high proportion of non-viable plant material that can bury the living fragments, thus reducing the success of their establishment. It is therefore preferable to limit as much as possible the collection to the top 5–10 cm, which also leave living plants behind and reduce disturbances to the root systems of ericaceous shrubs, allowing rapid donor site recovery.

Depending upon the device and the way plant material is collected, the size of fragments will differ, from big chunks to fragments less than 1 cm long. Campeau and Rochefort (1996) used 0.5, 1 and 2 cm fragments in greenhouse and field experiments and they found no significant effect of the size of diaspores on plant establishment. Besides fragment size, the methods of collection themselves may affect recovery. Boudreau and Rochefort (1999) compared the establishment of manually and mechanically collected *Sphagnum* fragments and their results show that *Sphagnum* plants collected manually established better than those collected mechanically. Our results concur (Figure 4). Boudreau and Rochefort (1999) assumed that the same quantity of fragments was spread and thus suggested that the mechanization may induce a stress. In our experiment (experiment 4), mechanical damage to the shredded fragments were obvious, with a resulting reduction in establishment success. It is obvious that a rototiller or any mechanical device may damage a certain quantity of plant fragments to a point that they loose their regeneration potential. It is however important not to automatically ascribe all differences between mechanized and manual reintroduction to mechanical stress. Indeed, during large scale operations, a proportion of the donor site material is not actually collected and remains behinds. Therefore, the actual density used for manual and mechanical reintroduction may be very different for a same targeted surface collected: surface restored ratio. From a practical point of view, some sort of mechanized equipment has to be used to collect the plant material. Hence, even if plant material undergoes a certain level of damage, the regeneration potential when using a rototiller for a large scale restoration project is still satisfactory (Figure 10). Other problems may arise at large scales when collecting plants as the machinery can sink and further damage the donor site. It is suggested to conduct the plant collection operation in the spring when the ground just started to thaw over the first 10 cm. Working with a frozen ground ensures that only the best regenerating plant material is collected and protects the donor site from severe damage. In fact, our observations show that when the ground is still frozen, the root system of ericaceous and other plants stay intact and allow for a rapid recovery of donor sites. Furthermore, mechanical collection operations tend to leave a large number of plant fragments on the donor site, and recovery of a *Sphagnum* colony from these fragments can be obtained within a few years of collection (Quinty and Rochefort, 1997).

Plant introduction

Limiting the impact of collecting plant fragments on undisturbed areas is an important consideration. It would not be wise to damage an area of undisturbed bog equal to the one being restored. The following question needs to be answered: 'Given one square meter of collected plant fragments, how large an area can be restored without substantially lowering the chance of successful plant establishment?'

The question of the density of fragments to be introduced has been addressed in terms of density of plants, in terms of *surface collected: surface restored* ratio and in terms of thickness of plant material spread. Number of fragments was used in the early development of the restoration approach (experiment 3). The results of the present study testing three densities of diaspores per square meter show that plant cover increases in accordance with the number of fragments introduced for most *Sphagnum* species. In these early experiments, optimum density of fragments per square meter was not reached, as demonstrated by the low cover values obtained after several years. Also, number of plants introduced per meter square were low compared to densities found in nature (Table 2), and probably far from sufficient to obtain a complete *Sphagnum* carpet within a reasonable period of time; meaning that the number of fragments introduced had to increase from what was tested initially in these early experiments (Campeau and Rochefort, 1996). For obvious reasons, using numbers of fragments to determine the quantity of diaspores to introduce is not possible at a large scale. Further experiments compared the quantities of plant material in terms of the

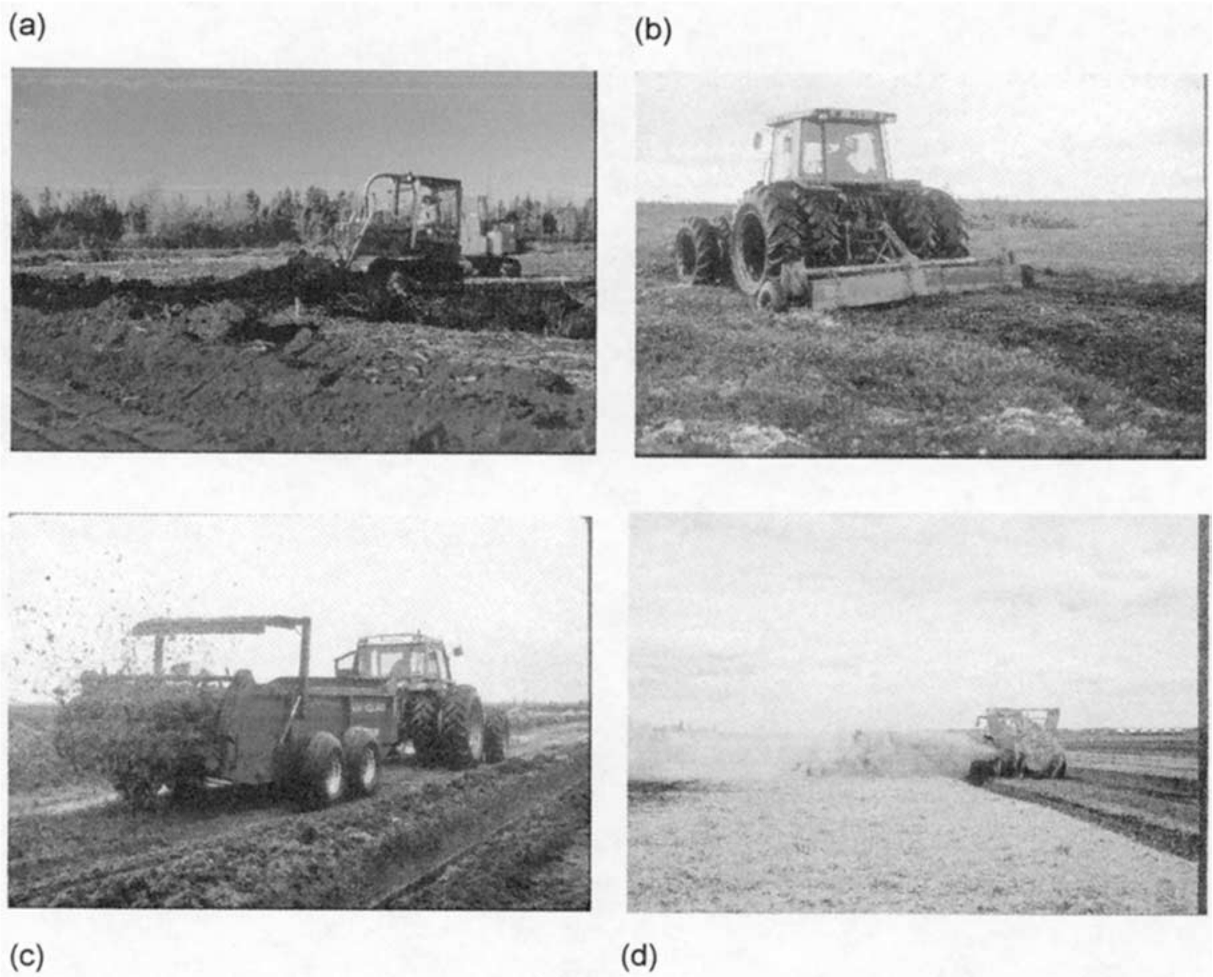

Figure 10. Application of the restoration approach at large scale. a) Field preparatation is the first step in the restoration operations. Depending on field starting conditions, diverse options are possible (see text) and different equipments are used, here a profiler collect surface peat into low bunds. b) Rototiller are frequently used to collect plant fragments because they do little damages to diaspores. c) Manure spreaders are ususally available from farmers at low cost. They allow spreading a thin continuous layer of fragments. d) Straw mulch is applied with a round bale processor that is more efficient than using small square bales.

ratio between the area collected and the area covered by the fragments after spreading. Ratios of 1: 10 to 1: 30 were used in several experiments. Estimates of the density of capitula per square meter allow comparison between numbers of fragments introduced and ratios (Table 2). For example, 450 fragments m^{-2} corresponds roughly to surface collected: surface restored ratios of 1: 100 for *S. fuscum* and 1: 40 for *S. magellanicum*. The results of the experiment comparing ratios of 1: 10, 1: 20 and 1: 30 (Figure 5) show an increase of the overall cover obtained at higher densities with total percent cover of 66, 51, and 48%, respectively, after five growing seasons. This suggests that using more plant material leads to a more rapid establishment of a total plant cover. Comparisons of experiments conducted at various sites under similar conditions (straw mulch) suggest that high percent covers do not solely depend on high density of reintroduction. For example, total cover reached 60% after two growing seasons at the Cromwell site, which had a mean water table 2.1 cm below the surface and where a 1: 10 ratio was used (Figure 8). Meanwhile, a cover of only 20% after three years was obtained at the Rivière-Ouelle site, where the water table remains around 50 cm below the surface on average (Figure 7). Although we cannot directly compare theses two experiments due to different conditions (climatic, species composition of plant material, etc.), it is clear that to minimize the impact on natural areas, efforts should go to raising the water table at the restored site if we want to make the best possible use of collected material and use lower reintroduction ratios.

However, the application of these results at a large scale had to be adapted to the use of machinery and ratios have been converted to the amount of plant material spread on bare peat surfaces. Plant fragments are spread on bare peat surfaces using a manure spreader (Figure 10). This device has been used because of its availability, its low cost, and its capability of spreading an even plant layer on large surfaces in a relatively short time. At large scale, early results showed that spreading too large a quantity of plant fragments decreases plant establishment success and that spreading a scattered layer of plants also decreases plant establishment success (Quinty and Rochefort, 1997). Total plant cover from the same experiment, after four growing seasons (experiment 6), confirms that the application of a thin layer of plant material gives the best result in terms of total plant cover and *Sphagnum* establishment (Figure 6). This amount, which is evaluated visually during the operations, corresponds roughly to a ratio of about 1: 15. Our observations support the fact that a field ratio of 1: 10 should actually be targeted to compensate for losses occurring when loading, transporting, and unloading the plant material from the donor site to the site to be restored.

Plant protection

Mulches for soil and plant protection are widely used in agriculture and well documented (Rosenberg et al., 1983). In peat bog restoration, Salonen (1992) used artificial plastic plants that increased soil moisture, decreased temperature, and allowed for higher seedling establishment. Grosvernier et al. (1995) studied natural plant succession on bare peat that lead to the reestablishment of *Sphagnum* carpets. They suggested that populations of *Polytrichum alpestre* and *Eriophorum vaginatum* could create microclimatic conditions favourable to *Sphagnum* establishment. Boudreau and Rochefort (1999) did find positive effects of plant populations (*E. vaginatum* and *E. angustifolium*) on *Sphagnum,* which they linked to higher relative humidity, lower temperature, and shading at the peat surface under populations of these species.

Several types of protective devices have been experimentally tested to improve microclimatic conditions on bare peat surfaces and provide a suitable environment to introduced *Sphagnum* fragments. Rochefort and Bastien (1998) tested the use of a perforated polyethylene sheet and two shade screens (40 and 60% shade) and they found a significant positive effect for both shade screens. They attribute this effect to higher peat water content, lower temperature, and lower light intensity measured under the shade screens. Rochefort et al. (1997) found that straw mulch enhanced the establishment of *Sphagnum* and other mosses compared to a plastic cover and the absence of protection. Longer term results for the same experiment (experiment 7) demonstrated that straw mulch is more efficient than shade screens (Figure 7). The positive effect of straw mulch on the establishment of *Sphagnum* fragments and other bog plant species has been demonstrated in many experiments performed by our research group (Rochefort, 2000). In fact, among the factors responsible for the successful establishment of *Sphagnum,* straw mulch seems to play a role as essential as water level. The results of the experiment testing the effect of straw mulch and *Carex* (Figure 8), clearly demonstrate that the straw mulch had a major impact even if the mean water table was at 2.1 cm below the surface. Price et al. (1998) showed that straw mulch decreases the water tension and the daytime temperature while increasing the relative humidity at the soil surface.

Straw has to be applied in sufficient quantity in order to be efficient. Our results show that 3 000 kg ha^{-1} is necessary to maximize the success of plant establishment. Lower densities also make a significant difference compared to the absence of protection, but colonization of bare peat by plants remains slow. It is unknown whether using more straw would result in higher plant cover, but visual observations revealed that plant fragments do not survive where straw mulch is thick and compact, probably because of a lack of light. It is also important to apply the straw mulch as soon as possible after the introduction of plant fragments because of the harmful effect of dry conditions on *Sphagnum* (Sagot and Rochefort, 1996).

Straw has the advantage, over the other types of cover, to be available almost everywhere at a relatively low cost. It also provided a better protection to plant fragments and it is easily applied with a straw spreader (Figure 10).

Season

Attempts have been made to determine the best season to conduct restoration work. We never considered that summer would be a good season due to the risk of drought that would threaten the survival of plant fragments. In the North American context, it is not realistic to conduct restoration operations during winter because snow cover renders the work with machinery difficult and also because plant material becomes frozen and cannot easily be manipulated.

In one of the two experiments comparing spring and fall introduction (Figures 8), we found no significant effect of season. In the second experiment where reintroduction at two time periods were compared (experiment 4) the results are inconclusive, as mulches were only applied in the spring to the fall-reintroduced diaspores. In many large-scale operations, other factors dictate the choice of the season. For instance, in very wet conditions at the donor site, it is preferable to work in spring when the ground is still frozen. At one site, we cleared the snow in winter to promote the penetration of the frost and provide a longer period of time to conduct the operations. Availability of workers and machinery also play a role at some sites.

Fertilization

Drained and mined peat bogs usually show low P and K concentrations (Proctor, 1992; WindMulder et al., 1996; Johnson and Maly, 1998; Wind-Mulder and Vitt, 2000), and NPK fertilisation is recommended in forestry for ombrotrophic peatlands (Paavilainen and Päivänen, 1995). In peat bog restoration, Salonen and Laaksonen (1994) reported very little effect of liming and NPK fertilization (25 g m^{-2}, 11-11-20) on vascular plants, while Money (1995) observed adverse effects of liming ($CaCO_3$ added until pH 4 is reached) but positive effects of phosphorus fertilization (7.5 g m^{-2}, NaH_2PO_4) on *S. cuspidatum* and *S. recurvum.* In North America, Rochefort et al. (1995) tested the influence of slow release NPK fertilizer and bone meal along with liming on *S. capillifolium* and they concluded that both types of fertilizers enhance the establishment of *Sphagnum.* Ferland and Rochefort (1997) fertilized plots where *Sphagnum* fragments had been introduced at a ratio 1: 20 in conjunction with companion species (herbaceous, ericaceous, and mosses) and they obtained significantly higher cover of *Sphagnum* and the other species. These authors suggested that fertilization could favour the establishment of companion species that would in turn facilitate the survival and multiplication of *Sphagnum* through modification of the microclimate. Phosphorus fertilization appears to help the colonization and stabilization of bare peat by *Sphagnum* and other bog species by favoring the establishment of nursing plants like *Polytrichum strictum.* Experiments are currently being conducted in order to determine the appropriate dose of this element and results should be published in the near future.

Conclusion

1. Field preparation is site specific as the appropriate option depends largely on site characteristics such as slope, existing drainage network, and peat thickness. It should include blocking of ditches and levelling of crowned fields. Bunds or dykes are suitable on sloping sites and should be combined with the use of overflow outlets to avoid flooding. Shallow basins or trenches successfully raise the water table and enhance water availability to *Sphagnum.*
2. Only the upper 10 cm of the surface of undisturbed bogs should be collected as plant material for restoration because there is a sharp loss of regeneration potential, with depth, for mosses.
3. The size of plant fragments has little or no effect on the regeneration potential of peat mosses. However, mechanical shredding of the *Sphagnum* mosses decreases their viability and regeneration potential.
4. The density/thickness of plant fragments spread on post-harvested fields is an important factor affecting plant regeneration. A thin but continuous layer of plant fragments, without much overlap, should be spread over the bare peat surfaces. This amount corresponds roughly to an actual ratio surface collected: surface restored of 1: 10.
5. *Sphagnum* and other moss fragments benefit from the presence of a protective straw mulch provided that it is applied at a density of about 3 000 kg ha^{-1}, and with appropriate equipment soon after plant reintroduction.
6. Spring and fall are the best seasons for conducting restoration work because they reduce the risk of drought and plant fragment desiccation.
7. Phosphorus fertilization increases the success of restoration by accelerating the establishment of bog plants, which could act as nursing plants for *Sphagnum* mosses as they grow, but the appropriate dose still has to be determined.

Acknowledgements

This article is the result of a number of research projects that were founded by the Ministère de l'Environnement du Québec, the Natural Science and Engineering Research Council of Canada and the Minnesota Future Resources Fund as recommended by the Legislative Commission on Minnesota Resources. We wish to thank the following industrial partners for their financial and logistic support and for sharing their knowledge in working on peatlands: Canadian Sphagnum Peat Moss Association, Québec Peat Producers Association, New Brunswick Peat Producers Association, Minnesota Peat Association, Acadian Peat Moss, Aitkin Agri-Peat, Berger Peat Moss, Fafard et Frères, Fafard Peat Moss, Lamèque-Quality Group, Lambert Peat Moss, Michigan Peat Company, Nirom Peat Moss, Premier Peat Moss, Sungro Horticulture. Numerous people participated in one or many experiments. We wish to thank Stéphanie Boudreau, Claude Lavoie and two anonymous reviewers for the helpful comments on the manuscript.

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