On the Use of Shallow Basins to Restore Cutover Peatlands: Plant Establishment

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Abstract

Since the early 1990s, restoration techniques have been developed for milled and cutover peatlands in eastern Canada. These techniques are based on the active reintroduction of peatland plant diaspores, blocking drainage, and the use of straw mulch to improve surface conditions. This study examines the effectiveness of using shallow (20 cm deep) basins of various widths to improve the success of current peatland restoration techniques. It comprises three different experiments, each spanning three or four growing seasons and combining both small-scale manual and large-scale mechanized plant reintroductions. Cover data recorded in two of the experiments were regressed against a series of environmental factors to determine how *Sphagnum* establishment success was related to abiotic variables such as moisture, water ponding, surface roughness, and mulch cover. Results of these experiments demonstrate that shallow basins were generally effective at promoting *Sphagnum* establishment and that this effect extends beyond the positive impact that basins have on hydrological conditions. Basins of various widths were equally successful. Soil-moisture content (linear positive effect) and duration and severity of flooding events (quadratic effect) were shown to be determinant of plant recovery. Other factors such as the density of straw cover (positive effect) and surface roughness (negative effect) were also instrumental in explaining local variation in *Sphagnum* cover. Plant cover after three and four growing seasons averaged 20–25% in mechanical reintroductions and 40–60% in manual reintroductions, demonstrating the overall effectiveness of the restoration techniques used.

Key words: **bog, ecological restoration, multilinear regressions, plant reintroduction, *Sphagnum*.**

Introduction

The extraction of *Sphagnum* peat from ombrogeneous peatlands (bogs) is a regionally important industry throughout northern countries of both Europe and North America. Hydrological, microclimatic, and ecological changes associated with peat harvesting deeply alter the original ecosystem functions (Wheeler & Shaw 1995; Price & Whitehead 2001). Once large-scale peat extraction stops, bare peat surfaces most often do not revert to typical peatland communities (Lavoie & Rochefort 1996; Campbell et al. 2002). Poor success in peatland vegetation reestablishment has been attributed to both lack of diaspores of the appropriate plant species (Salonen 1987) and the harsh hydrological and microclimatic conditions of the surfaces to be recolonized (Campbell et al. 2002; Price et al. 2003).

Beginning in the early 1990s, research to develop restoration techniques for peat-mined bogs was conducted in eastern Canada (Daigle & Gautreau-Daigle 2001). The techniques developed were based on the active reintroduction of peatland plant diaspores to cutover peat fields and on the use of various techniques to improve microenvironmental conditions for plant establishment (Rochefort et al. 2003). *Sphagnum* mosses, a key component of bog ecosystems, are able to establish new colonies after fragments of plants are spread on bare peat (Campeau & Rochefort 1996). Rewetting the abandoned peat surfaces by blocking the drainage ditches is a necessary step for restoration but is generally not sufficient by itself to ensure successful establishment of newly reintroduced diaspores. The use of mulches (Quinty & Rochefort 1997*a*; Price et al. 1998) and the presence of companion plant species (Grosvernier et al. 1995; Ferland & Rochefort 1997; Boudreau & Rochefort 1998; Sliva & Pfadenhauer 1999) greatly ameliorate the hydrological and microclimatic conditions on the peat fields, facilitating survival and growth of the newly reintroduced *Sphagnum* plants. Non-specialized machinery can be used to collect diaspores and to spread diaspores and mulches, making the use of these restoration techniques possible on large peat surfaces (Quinty & Rochefort 1997*b*; Rochefort et al. 2003).

Price et al. (1998) demonstrated that shallow depressions provided by bulldozer tracks or plough furrows are more suitable sites for *Sphagnum* recolonization than adjacent untreated surface because of important microclimatic differences. However, enhancing microtopography provided no overall benefit to the site to be revegetated as the corresponding positive relief elements became much less favorable for *Sphagnum*. This suggests that for

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revegetation success we need to create much larger (several meters wide) depressions, hereafter called basins, on cutover peat field. Shallow basins and adjacent peat ridges act to retain water in the spring or during rain events (Price et al. 2002). The enhanced site wetness should favor peatland plant recolonization. Improved water retention in basins, however, can lead to local water ponding at spring snowmelt or after important rain events, which in turn can negatively impact plant establishment (Quinty & Rochefort 2000; Rochefort et al. 2002).

This article presents the results of three plant reintroduction studies that were conducted over a 4-year period at a cutover peatland site in the Lac-Saint-Jean region, Québec. The objectives of these studies were to (1) determine whether shallow basins provide a significant advantage for the recolonization of *Sphagnum* mosses and other typical bog species, (2) evaluate whether the efficiency of moss establishment is related to basin configuration (size and depth), and (3) understand the relative impact of several abiotic factors on *Sphagnum* moss and other peatland plant recovery to further improve basin design and restoration techniques.

Methods

Study Area

The studies were performed in the Lac-Saint-Jean region, Québec, Canada (48°47′ N, 72°10′ W). The average annual temperature is 1.7°C, with average January and July temperatures of −17.1 and 17.3°C, respectively (Environment Canada 1992). Mean annual total precipitation is 906 mm (32% falling as snow).

The Sainte-Marguerite peatland is part of a 4,315-ha bog and fen complex, classified as plateau bog (National Wetland Working Group 1997). This study examined a cutover portion of the peatland located over a large bog-dominated area. The cutover sectors were drained for 2–3 years; then in 1991–1992 the upper 0.35–0.6 m was removed by block cutting with heavy machinery. This modern block-cut method differs from the traditional hand method in that, like with the milled peat extraction method, no plant diaspore is left on the peat field and extensive flat peat surfaces are left behind. Drainage ditches were blocked in 1993–1994 with peat dams of approximately 1-m width set every 100 m along the drainage system. Residual peat thickness currently ranges from 1.2 to 1.8 m and has suffered oxidation and subsidence due to drainage and cutting activities (Price & Schlotzhauer 1999).

Experimental Settings

Experiment 1: 1996 Manual Reintroduction in Small Basins and on Flat Surfaces. The objective of this experiment was to compare *Sphagnum* establishment between small basins and adjacent flat surfaces for three species of *Sphagnum*. This experiment was initiated in spring 1996 and designed as a split-plot experiment. Eight 8×12–m main experimental units were delimited on two peat fields. Four of these plots were left untouched, whereas the four others were prepared as basins. Basins were excavated in early spring 1996 using a bulldozer. The surface peat was scraped down to the frozen layer (20–25 cm), and the spoil was pushed into ridges bordering the basin on all four sides. Each main experimental unit was divided into three 8×4–m subplot units.

Within each main plot, one of the subplots was sown with *Sphagnum fuscum*, a second received *Sphagnum magellanicum* diaspores, and the third received *Sphagnum rubellum* diaspores (same species as *Sphagnum capillifolium* sensu lato in previous publications from the Peatland Ecology Research Group, Université Laval, Canada), species being assigned randomly. The taxonomy follows that of Anderson (1990). Plants to be used as diaspores were collected in early May 1996 in two nearby natural peatlands. Monospecific stands of the targeted species were selected, and the top portion of *Sphagnum* was collected by hand up to a depth of approximately 10 cm over a given surface (Campeau & Rochefort 1996). This material was handsown as diaspores on the experimental surface at a 1:10 ratio (1-m^2 surface collected in the natural area spread over 10 m^2 of experimental surface). All plots were covered with straw mulch immediately after sowing.

Experiment 2: 1996 Plant Reintroduction (Manual and Mechanized) in Basins of Various Widths. The second and most extensive experiment presented in this article was also established in 1996. It consisted of a series of large-scale mechanized reintroduction plots interspersed with smaller-scale hand reintroductions. The objectives of this experiment were to (1) determine whether shallow basins provide a significant advantage for recolonization of *Sphagnum* mosses and other peatland plants, (2) evaluate how basin design (namely, basin width) affects peatland plant establishment, and (3) evaluate how various abiotic factors affect *Sphagnum* recolonization success. Two species were used in this experiment, *S. fuscum* and *S. rubellum*.

Ten sections of peat fields (30×150 m) were prepared with basins (Fig. 1). Basins were excavated between 23 and 29 April 1996 using a bulldozer. The surface peat was scraped down to the frozen layer (15–25 cm deep), and the spoil was pushed into ridges bordering the longest side of 4-, 10-, and 20-m wide rectangular basins. The height and breadth of the ridges increased for the wider basins, ranging from 30 to 60 cm in height and from 1 to 2 m in width.

Basins were arranged either as a single basin occupying the medial portion of a peat field, thus being bordered by flat cutover peat surfaces on both sides, or as sets of parallel basins covering the entire width of the peat field on which they were established (Fig. 1). The latter arrangement is representative of how basins could be used in "real" large-scale field operations where the entire width of a peat field needs to be restored (Fig. 1A, 1C, & 1E).

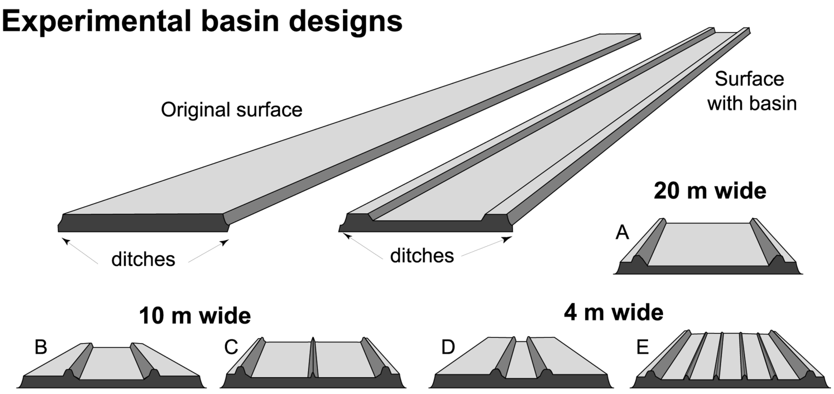

Figure 1. Illustration of the different width and arrangements tested in the field in the 1996 manual and mechanized reintroduction experiment (Experiment 2). Basins were 20 cm deep (vertical scale of illustration exaggerated) and were 4 m (D, E), 10 m (B, C), or 20 m (A) wide by approximately 200 m long. Basins were arranged either as single basins centered on the 28-m wide peat field (A, B, D) or as a group of basins covering the whole width of the field (C, E). Only one 20-m wide basin (A) would fit on a field.

The single-basin arrangement (Fig. 1A, 1B, & 1D), on the other hand, was added to assess how basins of different widths respond to seasonal and interannual water flows and storage (Price et al. 2002). One 20-m wide basin and bordering ridges (Fig. 1A) covered almost all the entire width of a peat field. Therefore, for the 20-m basin width, both the "real" operation scenario and the single-basin arrangement corresponded to a single central basin (Fig. 1A).

Plant reintroductions were made mechanically using the general large-scale reintroduction method described in Quinty and Rochefort (1997*b*) and Rochefort et al. (2002). Plant diaspores (fragments, seeds, spores, etc., of vascular plants and mosses) were collected in natural areas of the peatland. A total surface of 800 m^2 of plant material was collected from each of the *S. fuscum* and *S. rubellum* donor areas. This material was spread over approximately 16,000 m^2 of experimental basins, for a targeted surface-collected-to-surface-restored ratio of 1:10. Plant diaspores were spread in the experimental basins using a manure spreader, the two species being laid in separate strips along the length of the basins. Straw mulch was applied manually at a rate of 3,000–4,000 kg/ha immediately after plant reintroduction. Mechanized operations were completed by 1 May 1996.

Despite care taken to ensure uniformity, the use of a manure spreader to spread diaspores in large-scale operations results in densities that are more heterogeneous than with manual reintroduction. Density is an important factor in controlling *Sphagnum* establishment success (Campeau & Rochefort 1996), and we were concerned that random variations in densities resulting from mechanical operations might obscure some of the finer effects of basin design. Therefore, a small 10–20-m long section located at the mid-length of each basin was left aside for smaller hand-sown experimental plots. These hand-sown plots were prepared using the same techniques as in Experiment 1. For comparative purposes, four additional 15×15–m plots were delimited on separate cutover peat fields with no basins and were also hand sown. All manual plots were established between 2 and 8 May 1996 and covered with straw mulch immediately after.

Experiment 3: 1995 Mechanized Plant Reintroductions in Basins. The objective of this experiment was to assess how abiotic factors affect peatland plant recolonization success. Whereas Experiment 2 focused on the response of *Sphagnum* to abiotic factors, this experiment in addition examined the response of vascular plants and other mosses. Six parallel basins 3 m wide $\times$ 300 m long were prepared on three separate peat fields. Methods for basin preparation, plant collection, and diaspore spreading generally followed those described for Experiment 2. The surface-collected-to-surface-restored ratio was approximately 1:15. Diaspores collected from three natural areas were mixed together, with approximately 40% originating from an *S. rubellum*–dominated area, 35% from an *S. fuscum* area, and 25% from an *S. angustifolium* area. With the exception of one of the basins where straw was applied by hand, straw mulch was applied mechanically at a rate of 2,000–3,000 kg/ha using a manure spreader.

Measurements: Plant Establishment

Plant establishment success was monitored in all three experiments by visually estimating the percentage cover of *Sphagnum* mosses, *Polytrichum* mosses, herbaceous plant, and ericaceous shrubs on a series of 25×25–cm quadrats. Quadrats were distributed systematically along transects that ran at intervals across plots or basins. Plant cover measurements were conducted in the fall.

In Experiment 1, 24 quadrats were measured within each subplot in fall 1999. In Experiment 2 manual reintroduction, 12–30 quadrats were measured within each plot in fall 1996, 1997, and 1998 (numbers varied according to plot size and year). For the 1995 and 1996 mechanized reintroduction experiments (Experiments 2 and 3), the surface of each basin was divided into an imaginary grid made of cells 20–30 m^2 of surface (see *Submersion* in *Measurements: Abiotic Factors*). Moss cover in each grid cell was estimated in fall 1998 by sampling approximately one quadrat for each 2 m^2 of grid cell surface. Owing to time constraints, other moss and vascular plant cover estimates were made only for a subsample of these quadrats (three and six quadrats per grid cell for the 1996 and 1995 experiments respectively). For the 1995 and 1996 mechanized reintroduction experiments, estimates of *Sphagnum* percentage cover after one growing season were also taken but for a smaller total number of quadrats than in 1998.

Measurements: Abiotic Factors

Submersion. Water ponding in basins took place at spring snowmelt or sometimes after large rain events. To assess the importance of local ponding on a spatial basis, we divided basins in Experiment 2 into an imaginary grid made of cells 20–25 m^2 of surface (4×5–m cells for the 4-m wide basins; 5×5–m cells for the 10- and 20-m wide basins). In Experiment 3 basins, the grid cells covered 30 m^2 of surface (3×10 m). In Experiment 2, the width of the cells roughly corresponded to the width of the species strips for mechanized reintroduction, implying that each cell could be categorized as either an *S. fuscum* or an *S. rubellum* cell.

Semiquantitative estimates of water ponding were taken every week or second week during the 1996 and 1997 field seasons and used to calculate a relative submersion index for each grid cell. At each sampling date, an observer walked along each basin and assigned a 1-to-4 submersion value to each grid cell (1, <5% standing water; 2, 5–25% standing water; 3, 25–75% standing water; 4, 75–100% standing water). The final submersion index for each grid cell was calculated as the mean submersion value for the 10 sampling dates where a significant level of water ponding (i.e., submersion value >1) was noted for at least one cell of the whole experiment. Therefore, a grid cell with a high relative submersion index is likely to be flooded more often, more completely, and often deeper than a cell with a low submersion index. Likewise, a grid cell with a submersion index of 1, the lowest possible value for the submersion index, would be very unlikely to be underwater at any time during the growing season.

Water Content of the Peat. Volumetric soil moisture of surface peat was determined at different times in Experiments 1 and 2. Surface peat was retrieved with a cutter that sampled the upper 3 cm of soil. Three cutter volumes were removed and pooled to form a single sample for a total sample volume of 165 mL. All samples for a given sampling date were taken within a few hours. Fresh weight of each sample was recorded on the same day upon return to the laboratory, then samples were dried at 105°C and weighed, and soil moisture was calculated as milliliter of water per milliliter of soil.

In Experiment 1, samples were taken at regular intervals during the summer of 1996 to assess whether differences in soil moisture conditions existed between basins and flat surfaces. Three samples were taken from each of the main plots at every sampling date.

In Experiment 2, volumetric soil moisture samples were taken on 10 June and 1 and 22 August 1996 and 25 July 1997. On each sampling date, a series of transects 20 m apart were sampled across the width of every basin. One, three, or five peat samples (for the 4-, 10-, or 20-m wide basins respectively) were collected per transect. Soil moisture data from transects closest to each grid cell (see *Submersion* in *Measurements: Abiotic Factors*) were averaged to evaluate soil moisture for that cell. Additional sampling was performed in October 1998 on the hand-sown plots only, where a composite peat sample was taken directly from each hand-sown plot. Data from all sampling dates were averaged for each grid cell or plot to produce a soil moisture index value for that cell or plot.

Surface Roughness. Mechanical operations on partly thawed peat resulted in different surface conditions between and within basins. Some areas of basin bottom were totally flat, whereas other sections were covered with small ridges and depressions (up to 15–20 cm deep or high) resulting from the passage of bulldozer, tractor, and manure spreader. In October 1998, we assigned a semiquantitative surface-roughness value to each grid cell or plot of Experiment 2. These incremental index values were 1 (almost flat surfaces), 2 and 3 (increasing small-scale surface roughness), and 4 (numerous well-defined vehicle tracks).

Straw Cover. In Experiments 2 and 3, in addition to *Sphagnum* percentage cover, a semiquantitative index of initial mulch cover was estimated on each 25×25–cm quadrat measured in the fall of the first growing season. Straw mulch cover varied between quadrats because of local differences in application and because wind or water action caused local dispersion or accumulation of straw. Index values assigned to individual quadrats were 0 (<1% straw cover), 1 (between 1 and 25% of the surface covered with straw), 2 (between 25 and 75% of the surface covered with straw), 3 (thin straw cover on 75–100% of the surface), and 4 (thick straw covering the entire quadrat surface). These values were used to calculate a mulch density index value for each grid cell.

Statistical Analyses

In Experiments 1 and 2, plant cover data were analyzed using a split-plot design analysis of variance, with topography (basins and flat surfaces) being used as the main factor and species as split factor. Data were analyzed using the GLM procedure of SAS (SAS Statistical System software, v. 6.12, SAS Institute Inc., Cary, NC, U.S.A.). Plant cover data were log transformed prior to analyses. Peat water content data were compared between topography using analysis of variance, with time of sampling being considered as a repeated factor. For peat water content data, the analysis of residuals indicated that no transformation was required. Level of significance for statistical tests was set at 0.05.

In Experiment 2, plant cover over time, between species, and among basin widths was compared after the third growing season using standard analysis-of-variance procedures. Grid cells were considered experimental units. Cover data were log transformed prior to analyses to reduce heterogeneity of variances. Again, the GLM procedure of SAS was used to run the analyses and the significance level for statistical tests was set at 0.05.

For Experiments 2 and 3, regression analyses were conducted on the average 1998 cover data per grid cell to establish the relationship between plant cover and abiotic variables. Plant cover data were log transformed prior to analyses. All combinations of regression variables were compared, and the best subset of regression variables was selected using two criteria: the adjusted R^2 and Mallow's Cp (Draper & Smith 1981). Influential observations and outliers were detected using analysis of residuals, Cook's distances (Di), and Dffits and DfBetas statistics (Belsey et al. 1980). Once a data point was identified as potentially problematic, the multilinear regression model was run with and without that data point and the two outcomes were compared. This procedure resulted in the removal of one influential outlier from the *S. fuscum* manual reintroduction dataset of Experiment 2. Condition index values (Belsey et al. 1980) were used as a colinearity diagnostic test. These were calculated with the submersion variable centered to eliminate the colinearity generated by the presence of both the submersion index and its square value in the same model (Draper & Smith 1981). In all cases, condition index values were lower than 30, which is considered an acceptable level of colinearity in multiple regression models. All regression analyses and diagnostic tests were conducted using the REG procedure of SAS (SAS Statistical System software, v. 6.12).

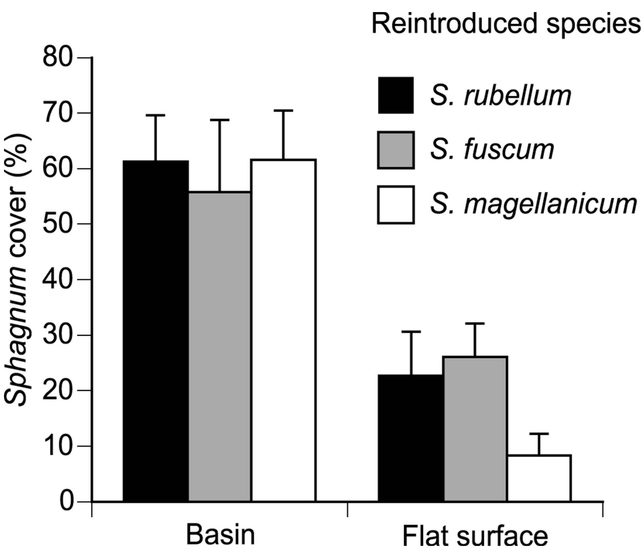

Figure 2. Effect of topography on *Sphagnum* establishment on peat substrates after four growing seasons (Experiment 1). The species–topography interaction is significant ($p = 0.002$), but percent cover was still significantly higher in basins than on flat surfaces for all three species tested ($p < 0.05$). Percent cover of *Sphagnum* was similar among species in basins ($p = 0.62$) but not on flat surfaces ($p = 0.003$).

Results

Impact of Basins on Peatland Plant Recolonization

Experiment 1: 1996 Manual Reintroduction. At the end of the fourth growing season, significant differences in *Sphagnum* cover were observed between basins and flat surfaces for all three reintroduced species (Fig. 2). Differences between basins and flat surfaces were more pronounced for *Sphagnum magellanicum* than for *Sphagnum fuscum* or *Sphagnum rubellum*. Indeed, although no significant differences in cover were observed among species in basins, *S. magellanicum* had a significantly lower success establishing on flat surfaces than the two other species.

The higher *Sphagnum* cover recorded in basins was compensated partly by a significantly better establishment of other moss species, mainly *Polytrichum strictum*, on flat surfaces (mean cover in basins: 2% in comparison with 5% on flat surfaces). Despite this, the average total bryophyte cover in basins (61%) greatly exceeded the average cover observed on flat surfaces (24%) after four growing seasons. Vascular plant cover also did not differ significantly between basins and flat surfaces after four growing seasons and was 5% on average.

Experiment 2: 1996 Manual and Mechanized Reintroductions. *Sphagnum* cover data collected over three growing seasons for manual reintroduction plots showed a significant increase over time for both flat and basin surfaces (Fig. 3A). This increase was faster for basins, with *Sphagnum* cover in basins always higher than that on flat surfaces (Fig. 3A). Percentage cover was significantly higher on *S. fuscum* plots than *S. rubellum* ones.

Cover also increased over time for mechanized reintroduction plots (Fig. 3B) but was generally lower than that on the manual reintroduction plots. Mechanical collection of diaspores may have left a larger quantity of diaspores on the donor site than manual collection, potentially resulting in a lower density of diaspores reintroduced for a same targeted surface-collected-to-surface-restored ratio of 1:10. In mechanized reintroduction plots, areas where *S. rubellum* was reintroduced had higher plant cover than areas with *S. fuscum* (Fig. 3B). We, however, believe that this difference can be simply attributed to technical problems at collection time: owing to operational constraints, *S. fuscum* source material was chunkier and

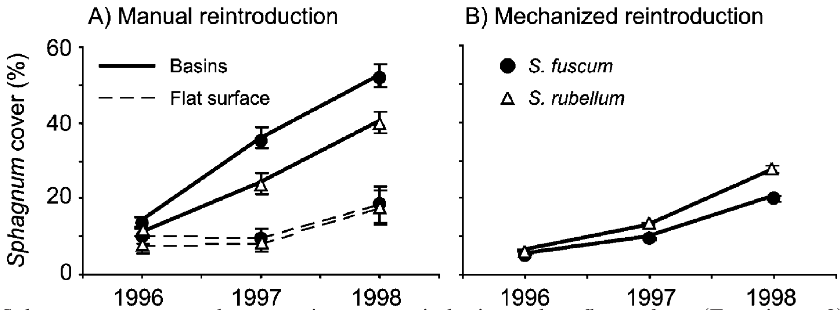

Figure 3. Development of *Sphagnum* cover over three growing seasons in basins and on flat surfaces (Experiment 2). The time–topography interaction is significant for manual reintroduction (A) ($p < 0.0001$), with percent cover significantly higher in basins than on flat surfaces for all 3 years ($p < 0.01$). Significant differences in time were also observed for mechanized reintroduction (B) ($p < 0.0001$). Significant differences between species were observed for both manual and mechanized reintroduction ($p < 0.0001$).

did not spread as evenly as *S. rubellum* diaspores, hence a lower establishment success.

After three growing seasons, significant differences in vascular plant cover could be detected between basin and nonbasin surfaces for manual reintroduction (mean cover 4 and 2%, respectively; data not shown). Mean cover of vascular plants in basins for mechanical reintroduction was 2.5%. Cover of mosses other than *Sphagnum* was generally small after three seasons and was not significantly affected by topography (2% for manual reintroduction and 1.7% for mechanized reintroduction).

Impact of Basin Configuration

Experiment 2: 1996 Manual and Mechanized Reintroductions. After three growing seasons, no significant differences in *Sphagnum*, other mosses, and vascular plant cover could be detected among basins of different widths for manual reintroductions. In mechanized reintroduction plots, 4-m wide basins generally performed slightly better than larger ones for *Sphagnum*, vascular plant, and total cover (data not shown). However, we believe this result to be mainly an artifact related to higher diaspore densities achieved in narrow basins due to the functioning of the manure spreader. In that sense, as mentioned in *Methods*, we consider manual reintroduction plots, where it was easier to ensure a more homogeneous diaspore density, to be a better test of the effect of basin width than mechanized reintroduction.

Impact of Abiotic Factors on Peatland Plant Recovery

Experiment 1: 1996 Manual Reintroduction. In Experiment 1, the use of basins resulted in wetter conditions for peatland plants to develop; volumetric water content of surface peat averaged 88% in basins in 1996, significantly higher than the 71% measured for flat surfaces over the same period (standard error of the mean, 2%). Reintroduction plots located in basins were flooded temporarily every spring during snowmelt as well as during summer or fall following periods of heavy rainfall. In contrast, flat surfaces were almost never covered with water or, if so, very locally. The enhanced plant establishment observed in basins could therefore be likely linked, at least in part, to improved site wetness.

Experiment 2: 1996 Manual and Mechanized Reintroductions. Basins in Experiment 2 were also generally wetter than flat surfaces and more prone to water ponding. Again, plant establishment from diaspores was enhanced in these wetter conditions. In this experiment, however, as in Experiment 3, the range of variation in plant cover and abiotic factor values among grid cells allowed for a more detailed examination of how several abiotic factors differed in their impact on *Sphagnum* recolonization.

To achieve this, we ran multiple factor regression analyses to evaluate which factor or combination of factors better explained the variation in *Sphagnum* cover between grid cells, that is, which regression model best explained the variation with a minimum of variables used. The factors we attempted to model in Experiment 2 were submersion, soil moisture, surface roughness, and density of straw cover. Regressions were run separately for each of the two species and for both manual and mechanized reintroduction datasets. Best-regression models selected to explain the local distribution of *Sphagnum* cover are presented in Table 1. Although the actual coefficient varied, general similarities can be detected between models. Water-related variables (submersion index and soil moisture) were predominant in all models (Table 1). Mulch cover played a role in explaining *Sphagnum* establishment for mechanized reintroduction but not for manual ones, whereas heterogeneity of the substrate had a minor effect in three of four cases.

For manual reintroduction, a significant quadratic relationship was found between the duration and severity of flooding versus percent plant cover after three growing seasons (Table 1). This implies that, when all other factors were kept constant, grid cells that were most likely to experience a certain degree of flooding developed a better moss cover than cells that were rarely flooded. The positive influence of limited flooding was more evident in

Table 1. Regression models that best explained the fall 1998 *Sphagnum* cover distribution among areas where peatland plant diaspores of two different species were reintroduced by hand or mechanically in spring 1996 (Experiment 2).

			Independent Variables					
Sphagnum Reintroduction	*n*	*Adjusted* R^2	*Intercept*	*SUBMERSION*	*SUB-Square*	*MOISTURE*	*ROUGHNESS*	*MULCH*
Hand-spread								
Sphagnum rubellum	39	0.34	−0.38 ± 0.51	0.94 ± 0.52 (0.09)	−0.26 ± 0.12 (0.12)	2.11 ± 0.83 (0.16)	−0.14 ± 0.07 (0.11)	—
Sphagnum fuscum	38	0.34	0.13 ± 0.49	0.36 ± 0.45 (0.02)	−0.14 ± 0.10 (0.06)	2.35 ± 0.71 (0.24)	−0.10 ± 0.07 (0.06)	—
Machine-spread								
S. rubellum	333	0.11	1.25 ± 0.21	0.12 ± 0.03 (0.05)	—	−1.06 ± 0.26 (0.05)	−0.04 ± 0.02 (0.01)	0.22 ± 0.05 (0.05)
S. fuscum	328	0.12	0.38 ± 0.21	0.11 ± 0.15 (0.002)	−0.07 ± 0.04 (0.01)	0.92 ± 0.23 (0.05)	—	0.08 ± 0.05 (0.01)

—, a variable not included in the regression model. Values are parameter estimate ± standard error. Values in parentheses are partial R^2 values. Independent variables that were modeled included: SUBMERSION, submersion index; SUB-Square, square of submersion index; MOISTURE, soil moisture index; ROUGHNESS, surface roughness index; MULCH, density of straw cover index.

S. rubellum than in *S. fuscum*, where the slope of the partial regression is smaller. For both species, moss cover, however, dropped when the likelihood of being subjected to frequent or severe flooding increased beyond a certain threshold (negative slope of the partial regression between the square of submersion index and *Sphagnum* cover; Table 1). Soil moisture generally had an important, linear positive effect on *Sphagnum* establishment (Table 1). Despite lower R^2, regression equations for mechanized reintroductions showed the same general trends in relation to water than manual reintroduction regressions. *Sphagnum* cover improved as soil moisture and flooding increased and then declined in grid cells with high submersion index (*S. fuscum*) or, in the case of *S. rubellum*, high soil moisture values (Table 1).

A noticeable difference between best-regression models selected for mechanized and manual reintroduction is that mechanized reintroduction models included mulch density, whereas manual reintroduction models did not (Table 1). This is most likely because mulch density among manual reintroduction plots was generally more even than for mechanized reintroduction plots (range of mulch density index was 2.8 for mechanized and 1.9 for manual reintroduction). However, if we group all individual quadrats measured in 1996 according to mulch cover values and calculate the average *Sphagnum* cover for each group (Fig. 4), the importance of mulch cover to *Sphagnum* establishment success becomes evident for both mechanized and manual reintroduction. When quadrats had either no straw cover or a very high straw cover, first-year *Sphagnum* establishment was poor for both species tested.

Experiment 3: 1995 Mechanized Plant Reintroductions in Basins. As for Experiment 2, the ranges of observations recorded among grid cells of Experiment 3 allowed us to model the importance of abiotic factors to plant establishment. This time, however, the regressions were run not only using *Sphagnum* data but also using vascular plant

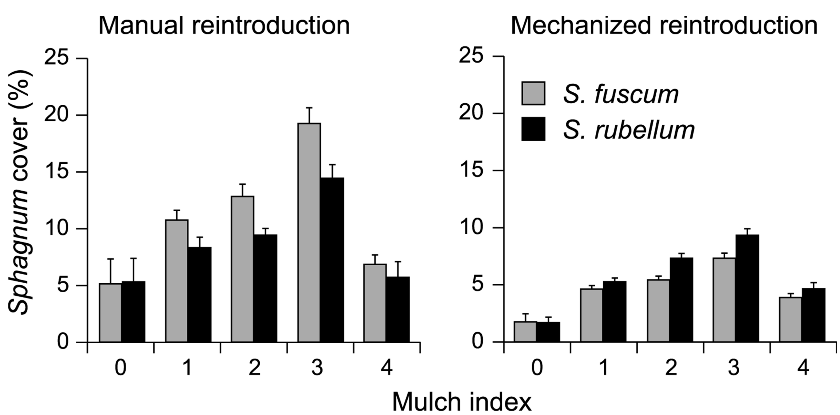

Figure 4. Effect of mulch cover on local *Sphagnum* establishment success as recorded in 25 × 25–cm quadrats after one growing season in Experiment 2 (n = 1,110 and 3,800 quadrats for manual and mechanized reintroduction, respectively). Mulch index: 0, less than 1% straw cover; 1, 1–25% of the surface covered with straw; 2, 25–75% of the surface covered with straw; 3, thin straw cover on 75–100% of the surface; 4, thick straw covering the entire quadrat surface.

Table 2. Regression models that best explained the fall 1998 plant cover distribution among areas where diaspores of two different species were reintroduced mechanically in spring 1995 (Experiment 3).

			Independent Variables			
Vegetation Component	*n*	*Adjusted* R^2	*Intercept*	*SUBMERSION*	*SUB-Square*	*MULCH*
Sphagnum mosses	130	0.18	−0.25 ± 0.21	0.51 ± 0.19 (0.05)	−0.12 ± 0.04 (0.07)	0.16 ± 0.04 (0.13)
Other mosses	130	0.28	0.39 ± 0.11	0.13 ± 0.11 (0.01)	−0.06 ± 0.02 (0.04)	—
Vascular plants	130	0.12	0.63 ± 0.13	0.25 ± 0.13 (0.03)	−0.07 ± 0.03 (0.05)	—
Total plant cover	130	0.2	0.63 ± 0.19	0.43 ± 0.16 (0.05)	−0.11 ± 0.04 (0.07)	0.13 ± 0.03 (0.1)

See Table 1 for a description of content, symbols, and variable names. Soil moisture index and surface roughness were not measured in this experiment.

and other moss data (higher number of quadrats per grid unit for these plants in Experiment 3 than in Experiment 2, which gave us more reliable grid cell means). Climatic conditions in the first growing season were widely different between this experiment and Experiment 2, which adds to the interest of this "repeat" analysis for *Sphagnum*. Indeed, although 1995 weather data showed precipitation well under the 30-year normal for the June-to-August period (total precipitation = 138 mm in comparison with the 279 mm normal), 1996 was a very wet year (total June-to-August precipitation = 344 mm).

Sphagnum cover developed more slowly in this mechanized experiment than in mechanized Experiment 2, with values after the first growing season reaching a mere 1%. Mean percentage cover after the fourth growing season (1998) nevertheless reached nearly 16% for *Sphagnum*, 2% for other mosses, and 6% for vascular plants, for an average total plant cover of 20%.

The factors we attempted to model in Experiment 3 were submersion and density of straw cover (soil moisture and surface roughness values were not available in this experiment). Best-regression models selected to explain the local distribution of plant cover are presented in Table 2. These models show that not only *Sphagnum* but also other mosses and vascular plants were significantly related to the submersion index. As for *Sphagnum* in Experiment 2, relationships between the different plant cover components and submersion had a quadratic element (Table 2), that is, although limited submersion was beneficial to plant establishment, severe flooding was detrimental.

Initial mulch density had a linear positive impact on *Sphagnum* establishment (Table 2). The partial correlation coefficient between mulch density index and *Sphagnum* cover is higher in this experiment (0.13) than for the 1996 Experiment 2 mechanized reintroduction (0.01 for *S. fuscum* and 0.06 for *S. rubellum*). Again, this is most likely because the mulch density indices were much more variable among the 1995 grid cells than among the 1996 ones (range of mulch density index = 4), which allowed for the local effect of too little or too much straw to become evident.

Is the Positive Response of *Sphagnum* to Basins Explained by Hydrology?

The two most influential factors reported from the regression analyses in Experiment 2 (i.e., soil moisture and likelihood of submersion) can be easily linked to

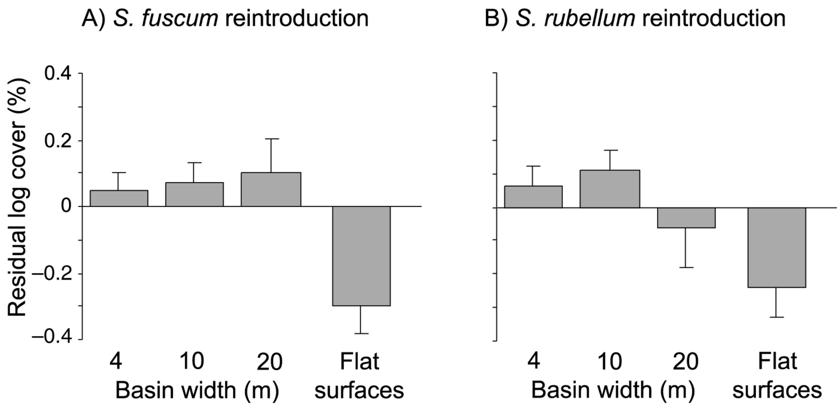

Figure 5. Effect of topography on *Sphagnum* establishment on peat surfaces after three growing seasons once the effect of soil moisture, submersion, surface roughness, and mulch cover was removed (Experiment 2). (A) *Sphagnum fuscum* reintroduction; (B) *Sphagnum rubellum* reintroduction. Data presented are residuals from multiple linear regression models explaining the distribution of *Sphagnum* cover in relation to abiotic variables (Table 1). Significant differences in residuals were observed between basin and flat surfaces but not among basins of different widths.

topography. Does that mean that the improved *Sphagnum* success in basins can be explained in terms of hydrology only? Can we still see differences in *Sphagnum* cover between basins and flat surfaces once we remove the effect of the moisture and ponding regression variables? To answer this question, we ran an analysis of variance comparing the residuals of the selected regression models between topographies. Significant differences between basins and flat surfaces were still present (Fig. 5). This result suggests that some unquantified factor(s) other than soil moisture, submersion, mulch, or surface roughness played a role in explaining the improved success of *Sphagnum* in basins.

Discussion

Results from the first and second experiments demonstrate that *Sphagnum* establishment is clearly favored in shallow basins in comparison with nonbasin surfaces. This improved plant establishment parallels the improved hydrological conditions observed in basins. Peat water content in basins of Experiment 1 was much higher than that recorded from nonbasin surfaces. Likewise, Price et al. (2002) (using same experimental setup as in Experiment 2) showed that the use of basins improved water table and soil moisture conditions of peat surfaces and resulted in a reduction of the frequency and duration of periods of capillary drainage (tensions smaller than -25 mb; Schlotzhauer & Price 1999). At this tension, intercellular pores of the poorly decomposed peat begin to drain and water availability for *Sphagnum* decreases (Price & Whitehead 2001).

Indeed, in Experiments 2 and 3, water-related variables were strong explanatory variables in regression models for factors affecting *Sphagnum* establishment. Reintroduction studies performed in controlled greenhouse conditions have demonstrated the strong relationship between *Sphagnum* establishment success and substrate humidity (Campeau & Rochefort 1996; Grosvernier et al. 1997; Buttler et al. 1998). Likewise, studies of spontaneous plant establishment of post-mined peatlands have shown that areas that are successfully recolonized with *Sphagnum* are often wetter than areas that are not (Smart et al. 1989; Lavoie & Rochefort 1996; Pfadenhauer & Klötzli 1996; Soro et al. 1999; Girard et al. 2002). What greenhouse studies and hydrological values fail to predict, however, is that there is an upper limit to the positive impact resulting from wetter conditions. When depth and water retention capacity of basins are enhanced to the extent where frequent or deep flooding occurs during part of the season, *Sphagnum* recolonization suffers some losses.

At the physiological level, Rochefort et al. (2002) showed that regenerating fragments of several species of *Sphagnum* not only tolerated but gained from shallow temporary flooding. Continuous flooding, however, had negative impacts on fully developed *Sphagnum* mosses. Some species, *Sphagnum rubellum* and *Sphagnum magellanicum*, for example, tended to form loose colonies of etiolated plants when subjected to long-term flooding. When water recedes and peat surfaces dry out, loose colonies would be more prone to desiccation than denser ones. Under similar flooding conditions, *Sphagnum fuscum* does not tend to etiolate as much as *S. rubellum* or *S. magellanicum*. This mechanism may explain part of the negative response to high submersion index we observed and give some indications of why *S. fuscum* seemed less affected by severe flooding than *S. rubellum* in Experiment 2.

In most field situations, it seems, however, likely that negative impacts of flooding on *Sphagnum* establishment are mainly related to physical disturbances. Quinty and Rochefort (2000) observed that severe flooding in a restored New Brunswick peatland led to problems of peat erosion and deposition in flood-prone areas, resulting in poor vegetation establishment success. Reduced *Sphagnum* colonization caused by water-level fluctuations and erosion is also reported in Sliva and Pfadenhauer (1999) and Tuittila (2000). Severe flooding of a freshly restored surface results in mulch displacement, erosion, burial of diaspores under depositional peat, and, in some instances, local destruction of water-retaining bunds. The larger the water body, the more chances of erosion by wave action. Impacts would also be more severe at sites where peat substrate is composed of fine, highly decomposed peat. Our experimental site, with its weakly humified peat substrate (degree of humification 3–4 on the von Post scale; Parent 2001), may have been even less susceptible to damages due to water movements than other sites, yet the negative effect of high levels of flooding on plant establishment was still apparent.

In summary, the overall establishment and growth response of diaspores reintroduced on flood-prone surfaces would be a balance between (1) the physiological response of diaspores and young mosses to being submersed for a certain period, which can be both positive or negative, (2) the gain obtained from growing in a wetter environment during the summer, and (3) the negative effect of physical disturbances associated with water and peat movements.

The use of mulches is considered a cornerstone of North American peatland restoration techniques (Quinty & Rochefort 1997*a*, 1997*b*; Rochefort et al. 2003). Mulches reduce evaporation from the peat surface and generally improve the moisture and temperature conditions for the establishment of *Sphagnum* mosses (Price et al. 1998). Indeed, when *Sphagnum* cover data recorded after one growing season were plotted against mulch cover values, the importance of an appropriate mulch density to ensure good *Sphagnum* establishment showed up very clearly. If some of our regression analyses showed little or no relation between mulch density index and *Sphagnum* cover at the grid level, it may be because the average straw cover was generally good and roughly comparable between grid cells, even though individual 25×25–cm quadrats may have locally lacked or hosted too much straw initially.

In three of four instances in our second experiment, surface roughness (which is akin to certain microtopography types tested in Price et al. 1998) was part of the regression model selected to explain *Sphagnum* response to abiotic factors. It is to be noted, however, that the influence of this factor was generally smaller than the influence of other factors present in the regression models. Price et al. (1998) examined the effect of surface microtopography on hydrological conditions that are determinant of *Sphagnum* establishment success. These authors showed that the presence of microtopography reduces overall moisture content of the peat surface but were unable to detect any significant impact of microtopography on the overall *Sphagnum* recovery after two growing seasons. In addition to affecting soil moisture, surface microtopography may indirectly affect *Sphagnum* by altering the local distribution of the protective mulch. In grid cells with many ridges and tracks, mulch tended to be unevenly distributed, with bare ridges adjacent to tracks thickly matted with straw, both conditions being detrimental to *Sphagnum* establishment.

Experiments 1 and 2 did not yield similar results for relative success of the different species of *Sphagnum*. Experiment 1 showed *S. fuscum* to be more successful in basins than *S. rubellum*, whereas Experiment 2 manual reintroduction did not. Basins in Experiment 1 were deeper and tended to retain more water than those in Experiment 2 (S. Campeau, spring 1997, personal observation). This may have provided a favorable, wetter environment that allowed *S. rubellum* and *S. magellanicum* to have establishment success equal to that of *S. fuscum*, a species that is generally more successful in restoration situations (Chirino & Rochefort 2000). The better performance of *S. fuscum* over *S. rubellum* in Experiment 2 manual reintroduction was not limited to cover. Waddington et al. (2003), reporting on the production rate and biomass accumulation of *Sphagnum* on restored sites, between 1998 and 2000 sampled a subset of plots from Experiment 2. They showed that mat thickness and accumulated biomass were greater in *S. fuscum* than in *S. rubellum*. On restored surfaces, *S. fuscum* is generally more efficient at retaining moisture during drought than *S. rubellum*, hence its better success (Campeau & Rochefort 2000).

A final, very interesting side result derived from regression models presented in this study is that differences in hydrological variables alone do not account for all variations in plant cover observed between basin and flat surfaces. One explanation is that removing the surface peat layer while preparing the basin resulted in a "clean" peat surface that was more favorable to *Sphagnum* establishment. Indeed, surface peat on cutover peatland is often covered by a nondescript crust made of algae, hepatics, and/or oxidized peat. Such a crust may impede water transport between the underlying substrate and the plants.

Conclusions and Restoration Implications

Our results show that the creation of shallow basins on cutover peat surfaces helped improve *Sphagnum* establishment success and generally had a positive impact on overall plant establishment. Indeed, after three to four growing seasons, *Sphagnum* cover was two to three times more developed in basins than on nonbasin surfaces. The gain of preparing shallow basins therefore seems worth the effort, especially considering that they represent fairly simple site manipulation.

Basins enhance water retention at the site and provide wetter conditions in which diaspores can develop (this study; Price et al. 2002). Regression models showed that hydrological factors are indeed very important determinants of *Sphagnum* success in basins. They also showed that increases in simple hydrological indicators (soil moisture and ponding) cannot be automatically considered a gain for peatland plants. Very high water-table levels, if they are associated with lengthy or deep flooding causing major disturbances on the surface, are detrimental to *Sphagnum* recovery. Maximum benefits were therefore not associated with maximum water levels but with intermediate values where the gain of increased site wetness balanced the potential drawbacks of flooding. To be efficient, basins should be designed to promote surface wetness in the summer, while minimizing the amplitude of water movements and flooding in the spring and fall. Extra benefits were observed when the bottom of the basin was devoid of tracks and ridges and when diaspores were spread evenly. Important to these factors was the provision of an adequate mulch cover and a suitable density of diaspores. Moreover, the impact of basins on *Sphagnum* recovery did not seem to be limited to the improvement in hydrological conditions: some additional benefits, such as a positive impact of reintroducing plants on a clean and fresh peat surface, are also suspected.

Although several factors can enhance or reduce *Sphagnum* establishment, our results show that the range of conditions for success is rather wide. This means that surface manipulations do not need to be extremely precise (e.g., targeting a very specific water level) to be effective. Likewise, variations within restoration zones (e.g., localized ponding of water) are not necessarily detrimental to the overall success. In that sense, peatland plant establishment on bare peat areas can be described as fairly resilient to local variations in conditions.

In the two large-scale mechanized reintroduction experiments presented here, overall vegetation cover reached 20–25% after three and four growing seasons. *Sphagnum* mosses (15–20% cover) were well distributed over the experimental surface, suggesting that with time these moss nuclei develop the potential for coalescing and covering the whole area. Vascular plant cover was composed of typical bog species and was quickly expanding (S. Campeau, fall 2000, personal observations). These results show that the peatland restoration techniques developed over the past 10 years in Canada can be quite effective and especially so when diaspore reintroduction and mulching and drainage blockage are combined with the use of shallow basins or low bunds (Price et al. 2003).

Establishment success in manual reintroduction plots was even greater than for mechanized plots (40–60% *Sphagnum* cover after 3 or 4 years), demonstrating that there is room for improved success as more experience is gained with mechanical operations.

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