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ARTICLE

Testing Protocols to Restore Disturbed *Sphagnum*-dominated Peatlands in the Hudson Bay Lowland

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Abstract Protocols for re-establishing *Sphagnum* mosses in disturbed peatlands are well established for southeastern Canada, but have not been extended to higher latitudes. We conducted two field experiments to examine how they could be applied to subarctic peatlands, disturbed by mining in the Hudson Bay Lowland, Canada. In a first experiment we tested microclimatic amelioration techniques including two local mulches, two commercial mulches and two densities of *Eriophorum vaginatum* as companion plants against controls. In a second factorial experiment, we tested whether *Sphagnum* could be spread during the winter onto frozen ground or snow, thereby allowing the mechanization of these techniques. The first experiment demonstrated that the spreading of *Sphagnum* fragments re-establishes a *Sphagnum* cover after 3 years, comparable to restored milled peatlands in southeastern Canada. However, no mulch was required, contrary to existing protocols. In the winter spreading experiment, *Sphagnum* capitula survived and showed similar densities during the first year as in the first experiment, but cover was substantially lower in the third year. A straw mulch helped establishment in the first year, but by the third season, control plots were no different from mulched plots. This study demonstrates that peatland restoration protocols can be extended to the Hudson Bay Lowland, and apparently simplified. Winter spreading is promising for the eventual mechanization, but further study is required to evaluate its scaling-up.

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Introduction

Sphagnum mosses play a key role in the ecological function of peatlands. They store large volumes of water and waterlog their environment (Hayward and Clymo 1982); they acidify their surroundings (Clymo 1984); and they decompose poorly (Clymo and Hayward 1982), allowing for peat to accumulate. *Sphagnum*-dominated communities consequently become the successional climax in boreal peatlands (Walker 1970). If *Sphagnum*-dominated peatlands are disturbed, the return of *Sphagnum* cover is required for them to recover these functions.

Recolonization by *Sphagnum* can be slow after severe peatland disturbances. It is especially slow following peat extraction (Poulin et al. 2005), mostly as a result of the harsh hydrologic environment offered by remnant peat surfaces after extraction ceases. The water table is lower, even once ditches are blocked (Price 1997), and less water is stored in the peat as a result of subsidence (Price et al. 2003). The humified residual peat also has smaller pore sizes, higher bulk density and lower specific yield, which is a measure of the water retention capacity when drained (Price 1997); consequent higher soil tensions limit moisture availability to *Sphagnum* fragments.

Several lines of evidence suggest that less severe disturbances, which only remove surface *Sphagnum* and leave bare peat, could also limit recolonization by *Sphagnum*. First of all, the delicate top 10 cm of a *Sphagnum* carpet has lower density, higher porosity and larger pores than underlying peats (Hayward and Clymo 1982), resulting in high specific yield (Schouwenaars 1993; Price 1996). Its removal would change the hydrological environment for recolonizing *Sphagnum* spores or fragments. Underlying peats also often have a lower albedo, so their exposure could increase the net radiation and the ground heat flux (Price et al. 2003); once dry, surface peats can heat up on hot summer days, and potentially add a heat stress to a drought stress for recolonizing *Sphagnum*. Furthermore, bare peat surfaces, unlike moss carpets, have intense surface frost heaving in fall and spring, creating extreme and persistent rough surfaces (Groeneveld and Rochefort 2005). This uproots seedlings, but it also produces rough microtopography that may limit capillary rise and reduce the contact of *Sphagnum* with the peat surface, exacerbating moisture and energy extremes. Finally, if disturbances are extensive, the large spatial scale could limit the availability of spores or fragments from nearby colonies, limiting *Sphagnum* recolonization.

Sphagnum mosses can re-establish vegetatively from their main stem, branches and leaves (Campeau and Rochefort 1996). This ability has led to the development of successful protocols for the large-scale restoration of severely-disturbed milled peatlands in the southern boreal and Atlantic maritime ecoregions of North America (Quinty and Rochefort 2003). Steps involve (i) spreading loose *Sphagnum* fragments taken from a local donor site; (ii) using a protective mulch cover to moderate surface microclimatic exchanges; (iii) adding a light rock phosphate fertilizer; and (iv) rewetting the site to increase both the water table and surface moisture conditions (Quinty and Rochefort 2003). The drained condition of milled peatlands allows for heavy machinery to be used to apply these protocols. High bryophyte cover, dominated by *Sphagnum*, can thereby return within half a decade or less (Rochefort et al. 2003; Chirino et al. 2006; Andersen et al. 2010). A straw mulch has proven to be the most effective protective cover (Rochefort et al. 2003), but companion plants such as cotton-grass tussocks and *Polytrichum* mosses can also encourage *Sphagnum* establishment (Lavoie et al. 2003; Groeneveld and Rochefort 2005). Disagreement remains on the optimal season for fragment introduction, with spring or fall introductions performing better in different experiments (Rochefort et al. 2003).

Severe peatland disturbance may be unrelated to peat extraction. In this study, we investigated the restoration of subarctic peatlands in the Hudson Bay Lowland (HBL) that were severely damaged during the exploitation of mineral resources. The HBL forms the third largest wetland in the world, extending along James and Hudson Bay from western Québec, through northern Ontario, northwest past Churchill, Manitoba (Riley 2011). A diamond mine recently began production in this region. Another roughly 6,000 km^2 within the HBL along its inland edge has recently been staked for mineral claims for precious metals and base metals, including the first commercial chromium deposits in North America (Far North Science Advisory Panel 2010); these mining projects are at advanced exploration and environmental impact assessment stages. Diverse disturbances to peatlands in these regions have occurred and are expected over the next half century related to these mining developments, including (i) fill placement on peatlands to build access roads, mine sites, processing plants and mining waste piles, (ii) clearing of peatlands for winter roads and runways, (iii) the burial of pipelines, and (iv) all terrain vehicle impacts. Mining proponents are required to place funds in trust to ensure the rehabilitation of impacted ecosystems at mine closure.

Our objective was to evaluate how existing peatland restoration protocols could be extended or modified to these subarctic peatlands disturbed during mineral exploration and exploitation. Differences exist between peatlands disturbed by peat exploitation to the south and those affected by mineral exploitation in the HBL that could affect the application of existing protocols. Those disturbed by mining in the HBL are not usually ditched and drained, so retain a high water table, although localized drainage can occur from mine dewatering. The higher water table may aid peatland recovery, but it prevents the use of heavy machinery for peatland restoration during the frost free period. Second, no peat is removed. Rather, these disturbances leave bare surface peat, roughly level with the surrounding peatlands, as in the case of winter roads and all-terrain vehicle trails, or after the burial of infrastructure such as pipelines. These bare peats are usually less humified, with inherent hydrological properties often more favourable for *Sphagnum* recovery. Third, these peatland disturbances, from our experience, are often linear in shape and relatively narrow, as opposed to milled peatlands, so propagule sources are nearby. Fourth, mine proponents avoid introducing non-native species, so straw mulch is problematic because of the potential introduction of non-native seed. Fifth, HBL peatlands have a much harsher subarctic climate with a short and cool growing season and with permafrost under most peatlands (Riley 2011). Finally, mine sites in the HBL are remote, currently only accessible by air except during mid-winter months, so local materials must be favoured during restoration.

In this study, we conducted two experiments to evaluate modifications of existing peatland restoration protocols to apply them in subarctic environments. The use of straw mulch was not feasible because of concerns for weed introduction, so we first evaluated the performance of alternative mulches and companion plants to moderate the surface microclimate and allow *Sphagnum* recovery. This would overcome contamination problems by non-native seed in straw mulch. We hypothesized that the peat-air interface would remain critical for *Sphagnum* establishment, as it is in southern boreal regions, and that a mulch or companion plants would be required to create a suitable microclimate, so we tested a range of commercial and local options. We also evaluated whether winter spreading of *Sphagnum* over snow or frozen ground was a feasible alternative to fall or spring spreading as is done on milled peatlands to the south. This would allow for the use of heavy equipment during restoration, and would allow larger scale applications of these protocols as is done in milled peatlands to the south.

Methods

Study Area

The study was conducted adjacent to the Victor diamond mine operated by De Beers Canada in the Hudson Bay Lowland region (52°49′ N, 83°53′ W; 83 m elevation). The mine began commercial operation in 2008 after a decade of feasibility studies and construction. It is only accessible by air or by winter roads over extensive peatlands. The region is a vast limestone plain overlain by glaciolacustrine and marine silts and 1–3 m of peat (Riley 2011). Topography is level, with a slope of ~1 m/km extending towards the coast. Peatlands cover over 98 % of the landscape and vary from carbonate-rich fens to mineral-poor bogs (Riley 2011). Pools are often present, and flark-string sequences are common in fens. Permafrost is discontinuous and underlies many peatlands (Riley 2011). At the nearest long-term climate station, (Lansdowne House; 52°14′ N, 87°53′ W; 280 km WSW; 254 m elevation; 1971–1989 data), mean annual temperature is −1.3 °C (January mean: −22.3 °C; July mean: 17.2 °C) with 1,244 growing degree days above 5 °C, and mean annual precipitation is 700 mm, over half of which falls from June to September during the growing season (Environment Canada 2010).

Two severely-disturbed sites in ombrotrophic peatlands were used for testing the restoration of *Sphagnum* covers: an abandoned all-terrain vehicle (ATV) trail and a bare peat section along a buried pipeline. Both sites met the criteria of having no surface vegetation and also would not be disturbed by continuing industrial activity. The ATV trail was used from ~2001 and abandoned in 2006. The surface vegetation was completely removed along a 6 m wide path by repeated use of tracked vehicles; some compaction of the peat may have occurred, but ruts were not evident. The pipeline was buried in winter 2006–2007, with a 15 m wide linear disturbance to peatlands. When the peatland was sufficiently frozen, a trench was excavated; the pipeline (~80 cm outside diameter) was inserted, and then immediately buried by excavated peat. The area directly above the pipe had mounded peat the following summer, but gradually subsided. The areas to each side of the pipe were level, but devoid of surface vegetation, from burial and scraping of the surface by heavy equipment (excavators, loaders, bulldozers and transport trucks). Study plots were located along these level areas devoid of vegetation, and not directly over the pipeline.

Both sites had fibric peat (H2 on von Post scale). Water chemistry was similar, as taken from water table wells, with pH 4.9 and 5.2 and conductivity of 45 and 123 *u*Scm^{-1} at the ATV and pipeline sites, respectively. Adjacent peatland vegetation at both sites had similar plant species richness, but composition differed slightly. Both sites were dominated by ericaceous shrubs (*Chamaedaphne calyculata*, *Ledum groenlandicum*, *Kalmia polifolia*, *Kalmia angustifolia* and *Vaccinium oxycoccos*), sparse herbs (*Drosera rotundifolia*, *Rubus chamaemorus*, *Eriophorum vaginatum*), *Sphagnum* and other bryophytes (especially *S. fuscum* and *Mylia anomala*), and lichens (*Cladina* and *Cladonia* species). The pipeline site had previously been burnt by a natural fire ~30 years prior to our experiment so had significantly fewer trees (*Picea mariana*), more *Vaccinium myrtilloides*, less *Sphagnum*, more *Polytrichum strictum* and more lichens (especially *Cladonia* and *Cladina*) than the ATV site.

A third site, an abandoned winter runway, was used as a donor site for *Sphagnum* fragments and *Eriophorum* tussocks and was also the experimental site for the first part of the winter spreading experiment. It consisted of a cleared strip of peatland, ~50 m wide by >1.5 km long along an east–west axis, on which woody vegetation and most hummocks were removed. It had bare peat or bryophyte and lichen carpets in shallow hollows, with *Eriophorum* tussocks, sparse ericaceous shrubs and no trees.

Mulch and Companion Plant Experiment

The experiment was set up as a completely randomized block design with six blocks, two at the ATV site, approximately 30 m apart, and four at the pipeline site, each 15–30 m apart. Each block consisted of eight 2×2 m plots, for a total of 48 plots. Plots within blocks were separated by 30 cm buffer strips with boards for walking. The plots received the following treatments: 1) no *Sphagnum* fragments and no mulch or companion plants; 2) *Sphagnum* fragments with no cover; 3) *Sphagnum* fragments with peat blocks; 4) *Sphagnum* fragments with local sedge mulch; 5) *Sphagnum* fragments with commercial coconut mulch (Terrafix® C32); 6) *Sphagnum* fragments with commercial straw mulch (Terrafix® S31); 7) *Sphagnum* fragments with low density *Eriophorum vaginatum* tussocks; and 8) *Sphagnum* fragments with high density *E. vaginatum* tussocks. The first two treatments were controls, the first to test the need for spreading *Sphagnum* fragments, and the second to test the need for a mulch. The peat blocks and sedge mulch were used as local alternatives to mulches. Peat blocks (~20×10×12 cm) were cut from nearby bare, fibric peat hummocks with a serrated knife and spread at a rate of 25 evenly-spaced peat blocks per 2×2 m plot. Although they are not mulches, we wished to test whether these peat blocks could increase surface roughness and create suitable microclimates for *Sphagnum*, in a similar manner as do tussocks of *Eriophorum vaginatum* (Lavoie et al. 2003). The sedge mulch was obtained from nearby natural stands of *Carex aquatilis* (60 cm tall) that were cut and applied at a rate of 1 m^2 to each 2×2 m plot. The commercial coconut and straw mulches were attached to a polypropylene net and were guaranteed to be weed-free. The commercial straw mulch was included as a close approximation of loose straw mulches used in restoration protocols developed for the southern boreal region (Rochefort et al. 2003). Finally, the *Eriophorum vaginatum* tussocks were used to test their effectiveness as companion plants, as recorded elsewhere (Lavoie et al. 2003). Tussocks with a 10 cm base diameter were randomly chosen. They were collected with a ~30 cm diameter root ball to ~30 cm depth and immediately transplanted into similar sized holes, either 50 cm apart in the low density *Eriophorum* treatment or 25 cm apart in the high density *Eriophorum* treatment. A light dose of bone meal (N:P:K ratio of 4-12-0; ~5 g) was added to the bottom of the holes to assure transplant success. Transplant success was 100 %.

Two *Sphagnum* species, *S. fuscum* and *S. fallax*, were spread on August 6, 2007. *S. fuscum* is common on peatland hummocks, whereas *S. fallax* is common in moist hollows (Riley 2011). Each species was collected from pure colonies to ~5 cm depth. They were bagged, refrigerated, then spread within 24 h in equal amounts over the disturbed peat substrates at a ratio of 1 m^2 of donor peatland to 16 m^2 of bare peat plots. The *Sphagnum* fragments were spread after planting companion plants and peat blocks or before mulches. Each plot was treated with rock phosphate (N-P-K, 0-2-0) at a rate of 30 $g m^{-2}$, similar to existing protocols (Quinty and Rochefort 2003).

Depth to the water level was monitored during the 2007 and 2008 growing seasons in two wells at opposite corners of each block. Volumetric water content was measured approximately twice a month in 2007 and 2008 growing seasons from all plots using a Delta-T® HH-2 moisture meter and WET sensor inserted diagonally to 3 cm depth. Calibration curves were determined for the WET sensor for each peat soil. Albedo was measured over plots from three of the blocks midday on July 18, 2008 under clear skies with a LI-COR® pyranometer and radiometer (LI-200 and LI-185B). Frost depths were measured periodically during the growing seasons in each experimental plot by pushing a 1.7 m by 2 cm steel pipe into the peat until an impenetrable frost layer was reached.

Numbers of live *Sphagnum* capitula were counted within six randomly-selected subplots (12.5×12.5 cm) within each plot on August 27, 2007 and on August 26, 2008. Capitula counts were used as a dependent variable to more accurately assess success after only one growing season. Subplots were marked with stakes pushed into the ground at the four corners of each subplot to allow us to recount the exact same areas. They were resampled on August 10–13, 2010, this time to determine the percent cover of *Sphagnum* and other bryophytes after three and a half growing seasons. Percent cover was determined by visual estimation.

Winter Spreading Experiment

This experiment took place over two experimental sites, the abandoned winter runway and the pipeline site. *Sphagnum* fragments were first exposed to extreme fall and winter conditions in mesh bags at the abandoned winter runway, and were then spread in the spring at the pipeline site. The use of mesh bags for fragments and this sequence of sites were preferred instead of direct spreading of fragments at the pipeline site. The mesh bags first prevented any loss of fragments from entrainment by wind or spring melt waters, which could have confounded the results in this small-scale field experiment. The abandoned winter runway also had no shrubs or trees, so provided an extreme of highly-exposed winter conditions for the fragments. Across both sites, the experiment was set up as a randomized block factorial experiment with four blocks, three fragment introduction times (November, January or March) and with or without a straw mulch cover.

Sphagnum fuscum and *S. fallax* were first collected by hand to ~5 cm depth on November 3, 2007 in proximity to the abandoned winter runway. Species were separated as individual fragments, mixed together and placed in the black mesh bags (25×25 cm; ~0.7 cm mesh) and stapled closed. Half the bags were wrapped with a single thickness of commercial straw mulch (Terrafix® S31). Bags of fragments were either immediately introduced into the experimental setup at the winter runway (November treatment) or placed in perforated plastic bags and stored in an unheated sea can container at ambient temperature until being introduced.

At the winter runway, each block consisted of two tripods made from steel poles to which bags of fragments were attached. Mesh bags with one of the six treatments were randomly assigned to one of the six poles within a block and attached with a loose tie wrap to allow them to move freely around the pole. Bags were introduced on November 3, 2007, January 28, 2008 and March 24, 2008. In November 2007, the ground was hard with frost but without a snow cover, while in January and March bags were placed on a snowpack of 15–20 cm and 15–25 cm, respectively. Mean snow densities across two profiles were 0.22–0.37 $g cm^{-3}$ in March (n=5). At a climate station within 5 km, air temperatures at 3 m height averaged −8, −19, −18, −20, −14 and

−3 °C in November and December 2007 and January, February, March and April 2008, respectively.

In early May, the bags were detached from the tripods, labelled, and transported to the buried pipeline site. The fragments were removed from the mesh bags and spread by hand on to 1×1 m plots of bare, at the same ratio as above, within the same blocks as on the winter runway. Treatments that were wrapped in straw mulch over the winter were covered with straw mulch after fragments were spread. A control treatment was also included that contained no *Sphagnum* fragments or mulch. All plots again received rock phosphate fertilizer (N-P-K, 0-2-0) at a rate of 30 gm^{-2}.

Water tables were monitored in one well per block, as above. The volumetric water content of surface peat in each plot was again measured approximately bimonthly during the growing season using the WET sensor. Live capitula were counted on August 27, 2008 in three randomly-placed 12.5×12.5 cm subplots per plot. Capitula counts were used in 2008 instead of percent cover to ensure accuracy. These same subplots were resampled on August 10–13, 2010 to determine the percent cover of *Sphagnum* and other bryophytes after three growing seasons.

Data Analysis

For both experiments, data were analyzed using univariate analyses of variance (ANOVA). Blocks were considered as a random factor, and other independent variables were fixed. Interactions among fixed factors were included in the model, but interactions with blocks were excluded. For the mulch and companion plant experiment, separate analyses were conducted for each dependent variable: albedo, volumetric water content, frost depths, number of *Sphagnum* capitula in August 2007 and August 2008 and the cover of *Sphagnum* and total bryophytes in August 2010. For the winter spreading experiment, separate ANOVA were conducted for *Sphagnum* counts and cover and for total bryophyte cover. These analyses were first conducted between the control versus all treatment plots, and secondly on factorial combinations of treatments. Tukey's *post-hoc* comparisons were used to evaluate significant differences. For all analyses, Type I error was set at α=0.05. All statistical tests were conducted using Statistica version 10.

Results

Mulch and Companion Plant Experiment

Mulches, companion plants and spread *Sphagnum* fragments increased the albedo relative to bare peat surfaces ($F_{7, 14}$=21.5, P<0.001; Fig. 1). The highest albedo occurred over mulches of sedge, coconut and straw and over high density *Eriophorum*. The depth of the active layer differed among treatments ($F_{7,35}$=4.3, P=0.002; Fig. 1) and reflected in part these differences in albedo. For instance, the three mulches, along with the peat block treatment, had the thinnest active layers. However, both *Eriophorum* transplant treatments had the thickest active layers, contrary to the albedo trend. The no-mulch and control treatments also had thick active layers.

Water tables were lowest in late August in both years, but they were much lower at the pipeline site than at the ATV site (pipeline Aug 2007: −30.4±2.0 cm, Aug 2008: −27.2±2.2 cm, n=8; ATV Aug 2007: −11.6±3.7 cm, Aug 2008: −3.9±1.0 cm, n=4). The volumetric water content (VWC) of surface peats in plots were also lowest in August 2008, and again lower on average at the pipeline site than at the ATV site (pipeline: 0.37±0.00 cm^3/cm^3, n=32; ATV: 0.57±0.01 cm^3/cm^3, n=16), but was not quite significantly different among the mulches and companion plant treatments ($F_{7, 35}$=1.4, P=0.09; Fig. 1), despite the differences in albedo and frost depths. The driest peats occurred on average under coconut mulch.

The initial density of *Sphagnum* capitula in August 2007 only differed between treatments with or without *Sphagnum* fragments (square-root transformed, $F_{7, 35}$=61.0, P<0.001; Fig. 1), with a mean of 31 capitula per 100 cm^2 in those that had received fragments compared to only 2 capitula per 100 cm^2 in the control treatment. By August 2008, after one growing season, capitula density increased across all treatments, but the only significant difference continued to be between the control with no fragments and the other treatments which had received fragments (square-root transformed, $F_{7, 35}$=17.0, P<0.001; Fig. 1). As such, mulches, whether local or commercial, or companion plants or peat blocks did not produce more *Sphagnum* capitula than treatments with no cover whatsoever.

By 2010, after two more growing seasons, *Sphagnum* cover differed between the control and the other treatments (square-root transformed, $F_{7, 35}$=8.9, P<0.001; Fig. 1). A similar result was apparent for the total bryophytes (square-root transformed, $F_{7, 35}$=11.0, P<0.001; Fig. 1). Treatments with fragments had on average 44 % cover by *Sphagnum* and 71 % total bryophyte cover, compared to only 8 and 26 % cover, respectively, in the control treatment. Common bryophytes besides *Sphagnum* included *Pohlia nutans*, *Polytrichum strictum*, *Dicranum* spp. and *Mylia anomala*. Treatments with straw mulch or *Eriophorum* tussocks had the highest mean *Sphagnum* cover, although they were not significantly different from the other treatments except for the control.

Winter Spreading Experiment

In the experiment on winter spreading, water tables during dry, late summer conditions (August 26, 2008) were 18.3±

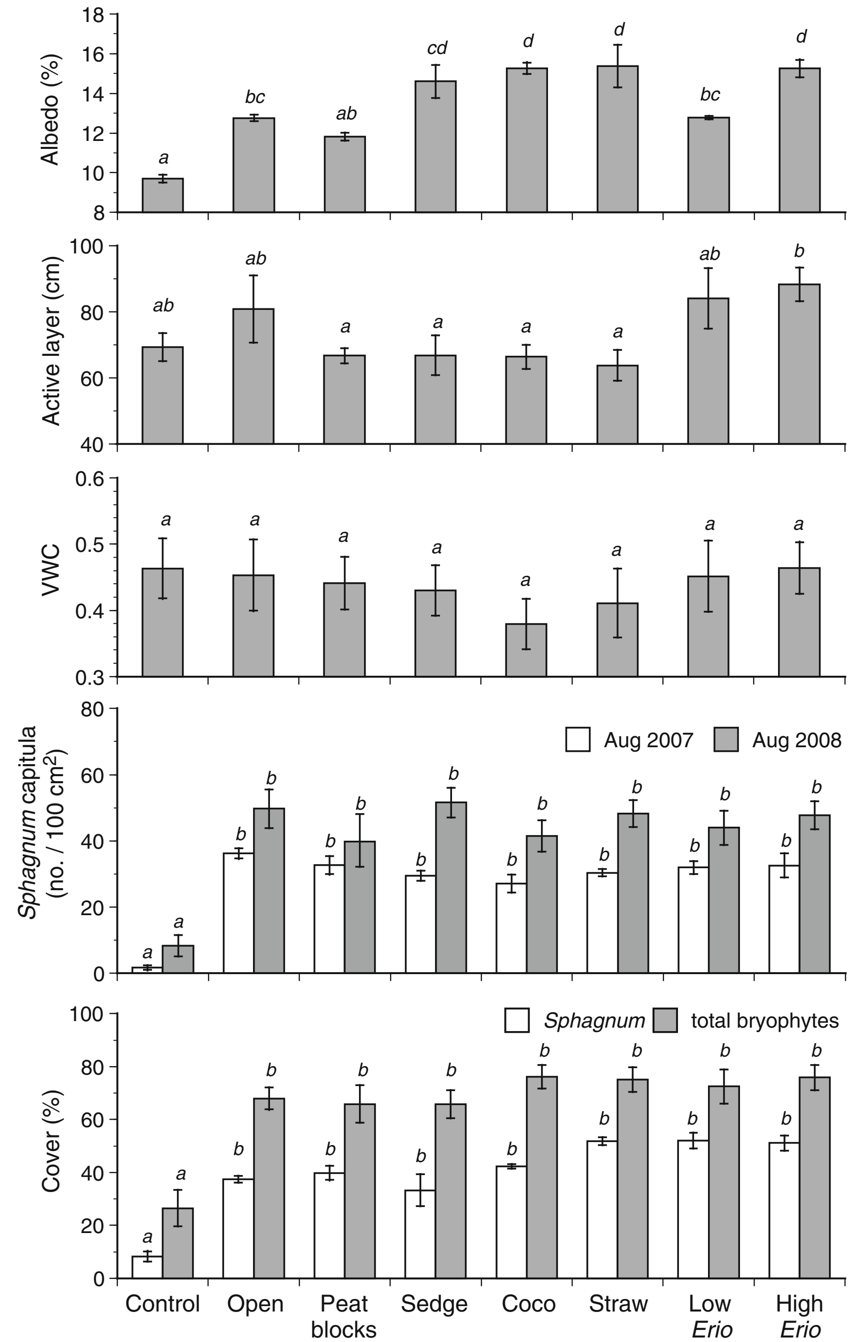

Fig. 1 Results of the companion plant and mulch experiment, showing albedo in 2008; volumetric water content (VWC) in August 2008; depth to frost in August 2008; capitula counts in August c and August 2008; and the percent cover of total bryophytes (*open bars*) and *Sphagnum* (*shaded bars*) in August 2010 for the different mulch and companion plant treatments (mean ± 1SE). All treatments except the control received *Sphagnum* fragments in the summer of 2007. *Letters* refer to significantly different treatments within that dependent variable, following a Tukey *posthoc* test ($P<0.05$)

3.1 cm below the surface, so higher than nearby plots for the mulch-companion plant experiment. Volumetric water contents were greater in the treatments without a mulch ($F_{1,15}=4.4$, $P=0.054$; no mulch: 0.38±0.03, mulch: 0.33±0.01, mean ± SE). No spreading month or interaction effects were found for VWC ($P=0.59$, $P=0.84$, respectively).

Initial *Sphagnum* capitula counts in June 2008 were much greater in plots that had received *Sphagnum* fragments compared to control plots, as expected, and they remained so in August 2008 ($P<0.001$; Fig. 2). For those that did receive fragments, the treatments of mulch, spreading month or their interaction did not affect the initial capitula counts in June 2008 (Table 1; Fig. 2), but by August 2008, those that had received a straw mulch had significantly more capitula than those without ($P=0.027$; no mulch: 19.7±5.3, mulch: 35.0±4.4). The spreading months did not impact capitula numbers, and no interaction was present. Note that in August 2008, capitula counts for the winter spreading experiment were about a third less than those in the mulch companion-plant study.

By August 2010, *Sphagnum* cover remained lower in control plots as compared to those that had received

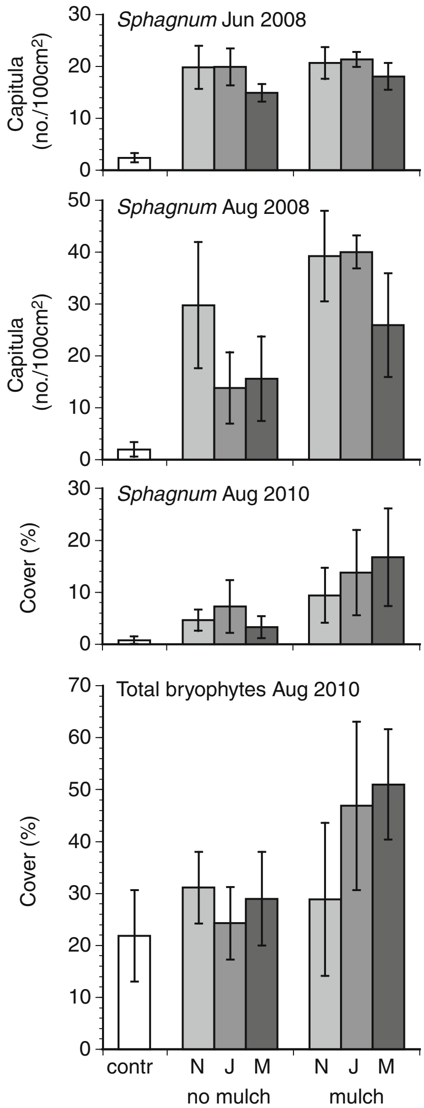

Fig. 2 Results of the winter spreading experiment showing counts of *Sphagnum* in June 2008 and August 2008 and the percent cover of *Sphagnum* and total bryophytes in August 2010 in plots with fragments exposed on November 3 2007 (*N*), January 28 2008 (*J*) and March 24 2008 (*M*), with or without a straw mulch. All treatments except the control received *Sphagnum* fragments

Sphagnum fragments ($P<0.045$). However, total bryophyte cover was similar between plots with or without fragments ($P=0.216$). The mulch no longer had a significant effect on *Sphagnum* as measured by cover, and spreading month and their interaction remained non-significant (Table 1). *Sphagnum* cover on plots that had received fragments was only about a fifth of that in the mulch and companion experiment (9.2±2.4 % versus 44.0±3.1 %, respectively). Total bryophytes did better, but their cover in the winter experiment still was only half as in the mulch and companion plant experiment (35.2±4.6 % versus 71.3±2.0 %, respectively).

Discussion

We were able to restore a *Sphagnum* cover on disturbed subarctic peatlands in the Hudson Bay Lowland. After three and a half years, our average *Sphagnum* cover in the mulch-companion plant experiment (44 %) was similar to average *Sphagnum* covers restored from fragments spread by hand on fibric peat in milled peatlands in the southern boreal shield ecoregion (15–40 %; Chirino et al. 2006). Bryophytes responded well in general. We had lower success in the winter spreading experiment, especially in terms of *Sphagnum* cover after 3 years (9 %), but we did not expect equivalent success rates considering the extreme conditions to which these winter-spread *Sphagnum* fragments were exposed.

Both experiments demonstrate that *Sphagnum* fragments must be introduced to these disturbed peatlands, as in other peatlands to the south (Campeau and Rochefort 1996; Rochefort et al. 2003). Otherwise, *Sphagnum* does not quickly recolonize. This is despite the fact that disturbances in our peatland sites were linear and narrow (6 to15 m wide) and surrounded by vast undisturbed peatlands. We observed *Sphagnum* with capsules nearby, so spores must be available for recolonization, but unable to establish, at least not quickly as large fragments.

Table 1 Analysis of variance of the winter spreading experiment for *Sphagnum* capitula counts in June and August 2008 and cover of *Sphagnum* and total bryophyte in August 2010. Cover data were square-root transformed to meet assumptions of the ANOVA. Effects in *bold* are significant at $P<0.05$

Source	df	June 2008 counts			Aug 2008 counts			2010 *Sphagnum* cover			2010 bryophyte cover		
		MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
Block	3	107	5.6	**0.009**	623	2.7	0.085	7.6	2.9	0.072	0.15	0.0	0.992
Mulch	1	20	1.0	0.325	1406	6.0	**0.027**	8.0	3.0	0.104	5.14	1.0	0.323
Month	2	42	2.2	0.144	378	1.6	0.230	0.2	0.1	0.917	1.73	0.4	0.710
Mulch*Month	2	3	0.2	0.852	177	0.8	0.484	1.3	0.5	0.621	3.05	0.6	0.552
Error	15	19			233			2.7			4.93		

The mulch and companion plant experiment showed that mulches or companion plants are not required for good establishment from fragments spread during the growing season, contrary to previous studies in milled peatlands with blocked ditches (Price et al. 1998; Rochefort et al. 2003) and to established restoration protocols in southeastern Canada (Quinty and Rochefort 2003). The winter spreading experiment, which submitted *Sphagnum* fragments to much more extreme conditions and had lower recovery, only showed a temporary effect of a mulch in the first year, which had disappeared by the third season.

Previous studies have shown that the successful *Sphagnum* recolonization of peatlands from fragments is strongly dependent on sufficient moisture in surface peats and the moderation of moisture and energy exchanges at the soil-atmosphere interface, especially during mid-summer drought (Price et al. 1998; Price and Whitehead 2001). Our disturbed peatland sites had higher water tables than in milled peatlands in the southern boreal shield, although the August mean water table of −30 cm at the pipeline site was similar to that in wetter years at control sites in the southern boreal shield (Aug 1996: −34 cm; Chirino et al. 2006). Volumetric water content is recognized as a better predictor of hydrologic conditions for *Sphagnum* (Price 1997), yet the mean August VWC of 37 % at the pipeline and 57 % at the ATV site were similar to control sites in the southern boreal shield (Aug 1995–1999 mean: 44 %, range: 22–67 %; Chirino et al. 2006). Although the late summer trough of moisture conditions is similar between bare fibric peats in the subarctic region of the HBL and those in the southern boreal shield, its duration may not be because of the shorter growing season. More frequent data is required to characterize the duration of moisture deficits as compared to the southern boreal shield ecoregions.

Mulches and companion plants moderate energy and moisture exchanges and reduce evaporation at the peat surface (Price et al. 1998). The short and cool growing season in these subarctic peatlands and the permafrost in the peats both likely limit the soil heat flux and evaporation, minimizing the need for mulches or companion plants. In our study, the lower albedo of bare peat surfaces appeared, in part, to increase the active layer. This seasonal thawing of the permafrost may increase surface moisture through capillary movement, thereby benefiting establishing *Sphagnum* fragments. In both experiments, volumetric water content was either similar or greater in plots without mulches, which is in striking contrast to peats with mulches in the southern boreal shield (Price et al. 1998). If moisture conditions for *Sphagnum* are adequate without a mulch, the increased solar energy may actually benefit their photosynthesis and growth.

Peat substrates differ between disturbed peatlands in this study and those from milled peatlands in southern boreal regions, which may have helped the recolonization of *Sphagnum*. The substrates in the study area were poorly decomposed (H2 on the van Post scale), in contrast to substrates of most milled peatlands (Chirino et al. 2006), so they would have higher specific yields and more favourable moisture environments (Schouwenaars 1993; Price 1996). We did not measure actual specific yields in this study or how compacted surface peats were as compared to adjacent peatlands. The compaction and potential subsidence of the substrate in these disturbed areas and the role of ground frost should be considered in future studies of peatland rehabilitation in this region.

The recolonization of *Sphagnum* in the winter spreading experiment, albeit more modest, indicates that heavy machinery could potentially be used to implement these modified protocols, once ground frost is sufficiently thick. However an important caveat remains to be tested; fragments were not actually spread on the ground during the winter, but rather were placed in mesh bags then on the ground. It is possible that these bags acted to insulate *Sphagnum* fragments from extreme cold and desiccation. Subsequent scaling-up of this modified protocol with the actual spreading of fragments onto frozen ground or snow is required to verify these results. Covering fragments with snow shortly after being spread could insulate them from these extreme winter conditions.

In conclusion, this study provides evidence that existing peatland restoration protocols (Quinty and Rochefort 2003) can be modified, and perhaps even simplified, for higher latitudes and in peatlands that were not disturbed by peat exploitation. *Sphagnum* fragments still have to be spread and a mild phosphate fertilizer applied, but our study demonstrated that a mulch or companion plants are not required. The winter spreading of *Sphagnum* fragments shows promise, thereby allowing the mechanization of the protocol, as is done in milled peatlands. Next steps must test the scaling up of these modified protocols, especially the mechanization and winter spreading. Disturbance to peatlands is expected to increase with increasing development in the high boreal and subarctic (i.e. (Far North Science Advisory Panel 2010). A primary goal must be to minimize any disturbance. However if inevitable, these modified protocols show promise for their restoration.

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