Polytrichum strictum as a Solution to Frost Heaving in Disturbed Ecosystems: A Case Study with Milled Peatlands

Elisabeth V. G. Groeneveld[1] and Line Rochefort[1,2]

Abstract

Substrate instability is a common problem in many disturbed ecosystems. In the case of milled harvested peatlands, the pioneer moss *Polytrichum strictum* is commonly found; it is well adapted to tolerate the harsh microclimatic conditions and peat instability of these sites. A field experiment was used to determine the effectiveness of *P. strictum* against frost heaving, a major type of disturbance on bare peat. Wooden dowels and fir trees (*Abies balsamea*) placed in a *P. strictum* carpet experienced almost no frost heaving, whereas heaving was severe on bare peat. Reintroduced *P. strictum* fragments thinly spread on bare peat reduced but did not eliminate frost heaving. Straw mulch (a protective cover often required in peatland restoration) effectively reduced heaving in the fall, but was less effective in the spring because it had partially decomposed. The *P. strictum* carpet, *P. strictum* fragments, and straw mulch reduced frost heaving by reducing the number of freeze–thaw cycles, by slowing the rate of ground thaw in the spring, and by reducing the unfrozen water content of the peat during the spring thaw. Different species of *Polytrichum* mosses should be considered for the restoration or regeneration of disturbed ecosystems where soil stability is problematic.

Key words: **bog, bryophyte, mire, nursing plant, restoration, substrate stability.**

Introduction

Disturbed ecosystems that have undergone profound changes, such as drainage and/or removal of vegetation, may remain devoid of vegetation for decades. Frost heaving, a form of substrate instability, limits plant recolonization in many disturbed ecosystems, including eroded blanket mires (Anderson 1997; Tallis 1997), bare soil in recently burned forests (Rietveld & Heidmann 1976), abandoned agricultural fields (Regehr & Bazzaz 1979), old field succession (Buell et al. 1971), the alplands of British Columbia (Brink et al. 1967), summit peats on the fells in Finnish Lapland (Luoto & Seppälä 2000), tussock tundra of the Arctic (Gartner et al. 1986), steep mountain lands in New Zealand (Dunbar 1974), the grassland steppe of the Pacific northwest (Sheley & Larson 1994), anthracite mining operations (Schramm 1958), and bare strip-mined soils (Woods et al. 1978, 1979). A solution to soil instability would therefore be useful for the restoration of many types of disturbed ecosystems.

Frost heaving occurs when soil water freezes into ice crystals or lenses near the surface of the soil. Soil water is attracted to the freezing front, promoting the growth in length of the ice crystals, which may raise a crust of soil by several centimeters in a single night (detailed in Groeneveld & Rochefort 2002). Reducing the moisture content of the soil is an effective way to control frost heaving. However, this solution is often incompatible with the goal of plant reestablishment in ecosystem restoration. Other methods used to reduce frost heaving, such as the use of chemicals, surcharge, mulch, snow pack, shade, and plant cover, are reviewed in Groeneveld and Rochefort (2002). In this paper, we focus on the use of plant cover because it is generally one of the final goals in ecosystem restoration. Plants such as alfalfa, mosses, trees, and grasses have been shown to reduce frost heaving in a variety of environments (Jones & Peace 1939; Larson 1960; Krumbach & White 1964). These plants, when used to reduce frost heaving to the benefit of other plants, may be considered as nurse-plants. A nurse-plant is a plant that facilitates the growth of a plant of another species during at least some part of its life cycle (Nuñez et al. 1999). Nurse-plant interactions are common in conditions of high physical disturbance, stress, or predation (Bertness & Shumway 1993; Hacker & Gaines 1997).

In the case of cutover peatlands (abandoned milled peatland), restoration by a paludification approach is often sufficient to reestablish a cover of bog vegetation within a few years (Rochefort et al. 2003). However, some restoration projects fail, and many of these failures are due in part to the instability of the surface, specifically frost heaving (Quinty & Rochefort 2000; Fig. 1). *Sphagnum* mosses are a key species in peatland restoration

[1] Groupe de recherche en écologie des tourbières and Centre d'études nordiques, Pavillon Paul-Comtois, Université Laval, Québec, Canada G1K 7P4
[2] Address correspondence to L. Rochefort, email line.rochefort@plg.ulaval.ca

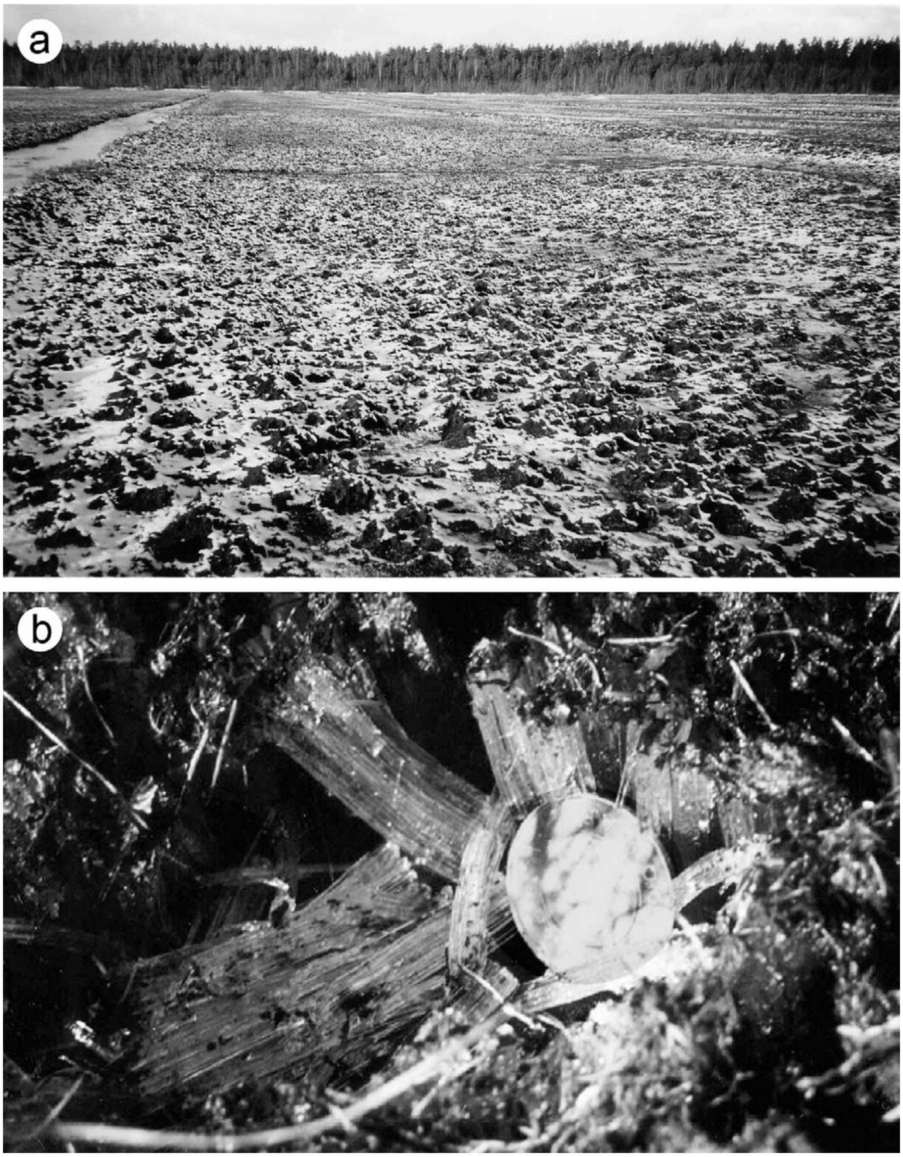

Figure 1. Frost heaving in peatlands. (a) Extensive effect on peat fields. (b) Close-up of peat material being raised by ice crystals.

(Rochefort 2000). However, they are poor pioneer species and substrate stabilizers and may be strongly impacted by frost heaving during their establishment. The use of a nurse-plant to facilitate the establishment of *Sphagnum* is one possible solution. Harvested peatlands are susceptible to frost heaving because their vegetation has been removed, they are in climates where freezing temperatures occur, and they are saturated with water in the spring and the fall. Because postharvested peatlands are particularly susceptible to frost heaving, solutions are needed to ameliorate the success of restoration projects; these solutions may also be used as a model for reducing frost heaving in other ecosystems.

The use of nurse-plants to facilitate vegetation growth in harsh conditions of milled peat bogs is receiving increased attention (Grosvernier et al. 1995; Buttler et al. 1996; Ferland & Rochefort 1997; Boudreau & Rochefort 1998; Robert et al. 1999; Tuittila et al. 2000). *Polytrichum strictum* is a pioneer moss present in and typical to *Sphagnum fuscum*–dominated communities in bogs (Reinikainen 1964; Salonen 1992; Buttler et al. 1996; Tuittila et al. 2000). It also grows spontaneously and abundantly on postharvested peat bogs (L. Rochefort & F. Quinty 2000, Université Laval, personal communication) and shows promise as a nurse-plant and peat stabilizer. The dense and uniform cover provided by this plant could potentially reduce frost heaving. One of the most interesting features of *P. strictum* is its stabilizing effect on loose soil. A dense coat of rhizoids covering the lower part of the stem captures fine wind-borne particles, stabilizing the surface (Leach 1931; Collins 1969). Once *P. strictum* has established on a site, it can enhance the growth of later succession plants such as conifers, various woody plants, and *Sphagnum* (Marsh & Koerner 1972; Buttler et al. 1996; Filion & Morin 1996). However, the mechanism by which *P. strictum* facilitates the growth of other plants has not been demonstrated experimentally. In this study we focus on the use of *P. strictum* as a means to alleviate frost heaving.

Methods

Study Area

The experimental site, Premier St-Laurent, is owned by a peat milling company. It is located near Rivière-du-Loup, Québec (lat 47°48′N, long 69°28′W), and was chosen for two main reasons. First, the physical characteristics and sparse vegetation were typical of vacuum-harvested sites in Québec. Second, hundreds of uprooted seedlings were scattered over the peat indicating that frost heaving was a major factor limiting revegetation; the few plants growing on the site which had survived frost heaving were often severely damaged. The surface of the peat showed the dimpling pattern characteristic of frost heaving.

The average annual temperature is 3.2°C, with average January and July temperatures of −12.2 and 17.8°C, respectively. Local annual precipitation averages 924 mm, of which 73% falls as rain (Environment Canada 1993). The peatland is part of a 3,375-ha bog–poor fen complex, classified as a "domed bog" (National Wetlands Working Group 1997). The study site, a 4.4-ha section of the bog, was vacuum harvested for approximately 10 years and then abandoned in 1980 (J. Gagnon 2000, Premier Tech, personal communication). The residual peat layer is more than 2 m thick. With time, the drainage ditches have partially filled in, but the blockage is incomplete and the site is very dry. During the months of July and August, the water table averaged 66 cm below the surface.

Although 20 years have elapsed since the site was last harvested, vegetation is sparse. Tussocks of *Eriophorum vaginatum* var. *spissum* Fern. are evenly scattered over the site. Ericaceous shrubs such as *Vaccinium angustifolium* Aiton., *Ledum groenlandicum* Oeder., *Kalmia angustifolia* L., *Rhododendron canadense* L., and *Chamaedaphe calyculata* L. are present in small numbers. Also present are small trees such as *Betula papyrifera* Marsh., *Abies balsamea* L., *Larix laricina* (Duroi) K. Koch., and *Picea mariana* (Mill.) B.S.P. and a few other vascular plants, lichens, and mosses. *Polytrichum strictum* is the dominant moss, forming large circular colonies especially around the *Eriophorum* tussocks. *Sphagnum* is rare, being sporadically present in or near ditches. Together these plants cover approximately 10% of the total area.

Treatments and Experimental Design

Three types of *P. strictum* cover were tested against frost heaving: carpets, fragments, and none. The carpet treatment was designed to represent naturally occurring colonies of *P. strictum*. The fragment treatments were chosen to test the effectiveness of North American bog restoration techniques against frost heaving. In this method, shredded plant material which has been harvested from a healthy bog is spread over the surface to be restored (Rochefort 2001). Because straw is already used in restoration to protect moss diaspores from desiccation, and has been shown to reduce frost heaving in an agricultural setting, we tested the three types of *P. strictum* cover in a factorial arrangement, with and without straw.

The experiment was initiated in May 2000 and ended in October 2001. A complete randomized block design with six blocks was used. Within each block, each experimental unit (plot) measured 1.5 × 1.5 m and was separated by at least 1 m from its nearest neighbor. Metal rods (diameter = 1 cm, length = 2 m) were inserted 1.5 m into the peat to delimit the corner of each plot. All existing vegetation and debris were removed from the plots, and the peat surface was smoothed with a garden rake before applying the treatments. The resulting smooth peat surface had the appearance of a freshly abandoned peat field. A wooden boardwalk was installed between the plots to minimize trampling.

Application of Treatments

The *P. strictum* carpet was collected from postharvested peatland and reintroduced in squares measuring 25 × 25 cm. The average length of the *P. strictum* stems was 2.6 cm. An average of 2.3 cm of peat was left under each square to hold the carpet together for transport. Before planting the squares at the experimental site, the top 2 cm of peat was removed from each experimental unit that was to receive the squares, to compensate for the adhering peat. Nine squares were planted contiguously in each of these experimental units, so as to recreate the appearance of a natural moss carpet.

Polytrichum strictum for the fragment treatment was also obtained from the same region as in the previous treatment. A lush carpet of *P. strictum* was selected, and the stems were clipped flush with the peat surface. The average fragment length (entire stem of individual *P. strictum* plants) was 7.9 cm. Natural carpet fragments measuring 0.225 m^2 each were spread over each 2.25-m^2 plot (i.e., in a 1:10 ratio). This is a ratio commonly used in the North American method of peatland restoration (Quinty & Rochefort 1997; Rochefort 2001).

Straw was applied by hand, at the rate currently used in peatland restoration, 3,000 kg/ha (Quinty & Rochefort 1997). In plots where there was both *P. strictum* and straw, the straw was spread over the *P. strictum*. Fine plastic meshes with a porosity of 97.5% were lightly laid over the straw to prevent it from blowing away; they were removed during the summer of 2001. The mass and structure of the straw is such that any possible effect of a light plastic net is expected to be minor in comparison with that of the straw.

Estimation of Seasonal Frost Heave

Fir seedlings and wooden dowels were used to estimate the frost heaving. In each plot, eight small fir trees (*A. balsamea*) were planted in the peat. Fir trees were chosen because seedlings were abundant on the site and easy to transplant. They were also clearly susceptible to frost heaving damage. Trees with only one shoot (no branches) and not more than two brown needles were transplanted. The average shoot length was 4.2 ± 0.6 cm (SD), the average root length 9.9 ± 2.8 cm (SD). To plant the fir trees in bare peat or on the surface overlaid with *P. strictum* fragments, we dug a little hole, gently inserted a tree, refilled the hole, and replaced the *P. strictum* fragments at the normal density around the seedling (for the fragment treatment). To plant in the carpet, we dug out a plug of *P. strictum*, placed the tree in the resulting hole, and pushed the plug back in place. Although we were as gentle as possible, this plug planting method evidently caused some trauma to the seedlings. In addition to the fir trees, 16 wooden dowels, 0.64 cm in diameter and 14.8 cm in length, were inserted 10 cm into the peat in each plot. To measure the vertical displacement due to frost heaving, sturdy posts (2-m metal rods) were driven into the corner of each plot (4 per plot). Two straight metal bars were then clamped to the corner rods 10 cm above the peat surface. A third metal bar slid along the two clamped bars. A ruler was used to measure the distance from this slide and the top of each fir seedling and dowel, on 24 August 2000, before any frost heaving occurred. This distance was remeasured on 7 November 2000 during the fall heaving season, and again on 29 May 2001, after all heaving was over the following spring. The method described is similar to that of Decker and Ronningen (1957) and Portz (1967).

Phosphorus fertilizer (phosphate rock) was applied at a rate of 150 kg/ha to enhance the establishment of the *P. strictum* carpet and fragments and fir seedlings. This is the same amount currently recommended for the restoration of peat bogs (Rochefort 2001). All plots with *P. strictum* were hand watered with 56 L of bog water during the first 2 weeks after they were planted; the other plots received 32 L over the same time period; this difference is not expected to affect frost heaving results because 3 months elapsed before heaving started.

Environmental Variables

Temperature was monitored in four treatments: carpet, fragments, bare peat, and straw. Soil temperature was measured using a StowAway datalogger (Onset Computer Corporation, Pocasset, MA, U.S.A.) with an external sensor buried 1.3 cm below the peat surface. Measurements were taken every half-hour from 19 to 30 October 2000 and every hour from 26 April to 11 May 2001. Five replicates (dataloggers) were installed for each treatment in 2000 and two replicates per treatment in 2001.

Unfrozen volumetric soil moisture was measured using time domain reflectometry (TDR), after sundown on 29 April 2001. TDR works by measuring the transmission time of an electrical pulse along two (or more) waveguides that are inserted into the peat. In each plot, TDR probes with two 30-cm-long parallel waveguides were inserted for their full length angled from the peat surface to the thaw line, to obtain the average unfrozen soil moisture reading for each plot. Soil moisture values were read directly from the display of a Campbell Scientific 21X Micrologger (Campbell Scientific, Inc., Logan, UT, U.S.A.). Three readings were taken from different locations in each plot, the average being used for the analysis.

Depth to the thaw line was measured in the evening of 25 April 2001, a few days after the snow cover had melted, and in the early morning hours of 30 April 2001. A slender rod was pushed vertically into the unfrozen peat until the thaw line was reached, and the depth was recorded (Rydén & Kostov 1980). Cracks in the thaw line, where there was no longer any ice, were avoided. Five depths were taken per plot, the average being used for the analysis.

Statistical Analyses

Vertical movement of dowels and fir seedlings, health of fir seedlings, volumetric soil moisture, and depth to the thaw line were analyzed with an analysis of variance (ANOVA), using the GLM procedure of SAS (SAS Institute Inc. 1988). In all cases, main effects of straw and *P. strictum* cover were tested, as was the interaction between the two. Where the interaction was significant, only the interaction was interpreted, and statistical results are presented only for the interaction. Where there was no interaction between the main effects, a Tukey multiple comparison test was done on the means of each factor averaged over all the levels of the other factor (Sokal & Rohlf 1981). Where there was an interaction between the main effects, the Tukey multiple comparison test was limited to comparing the means of one factor within each level of the other factor. The Tukey multiple comparison test was chosen because it is a relatively severe test which minimizes type I error. The data for the frost heaving of fir seedlings in the spring were log transformed to reduce heterogeneity of variances. All tests were considered significant at $p \leq 0.05$.

On 24 August 2000 three plots were randomly chosen, and the position of each dowel and fir was remeasured. The average of the absolute value of the difference between the first and second measurements was calculated. This value, 0.36 cm for the dowels, and 0.39 cm for the fir seedlings, is considered the measurement error. Any frost heaving value between ±0.36 cm for the dowels and ±0.39 cm for the fir seedlings is therefore considered to be zero.

Results

Heaving of Dowels and Fir in Fall 2000

In fall 2000 a significant interaction was found between straw and *Polytrichum strictum* (Fig. 2). The dowels did

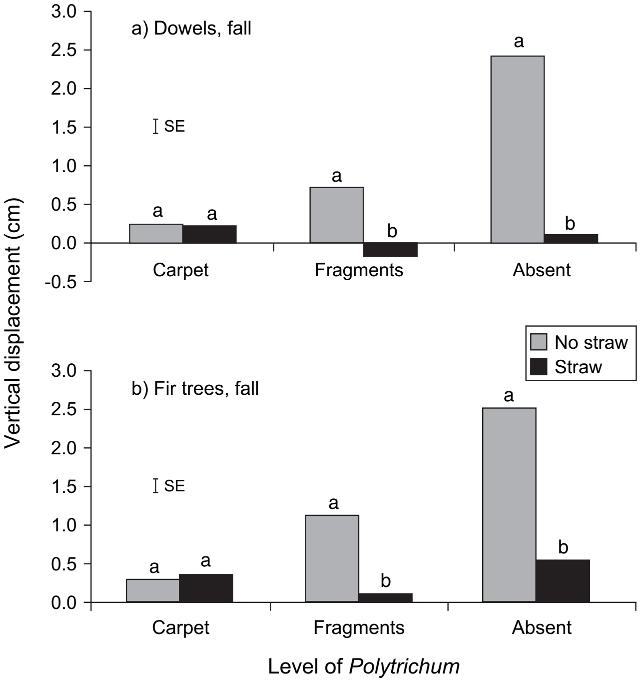

Figure 2. Vertical displacement of dowels and fir trees in fall 2000 (cumulative frost heave from 24 August to 7 November) due to frost heaving on an abandoned vacuum-harvested bog, at Premier St-Laurent, Rivière-du-Loup, Québec. (a) Dowel heave in the fall. $\text{ANOVA}_{\text{Straw}*Polytrichum}$: $df = 2$, $F = 16.43$, $p < 0.0001$. (b) Fir tree heave in the fall. $\text{ANOVA}_{\text{Straw}*Polytrichum}$: $df = 2$, $F = 13.85$, $p < 0.0001$. For both (a) and (b), values followed by different letters are significantly different at $p \leq 0.05$ by the Tukey test for straw effect within each level of *Polytrichum*; Tukey for *Polytrichum* levels when straw is absent: Carpet = a, fragments = a, absent = b; Tukey for *Polytrichum* levels when straw is present: carpet = a, fragments = a, absent = a. SE = standard error of the means.

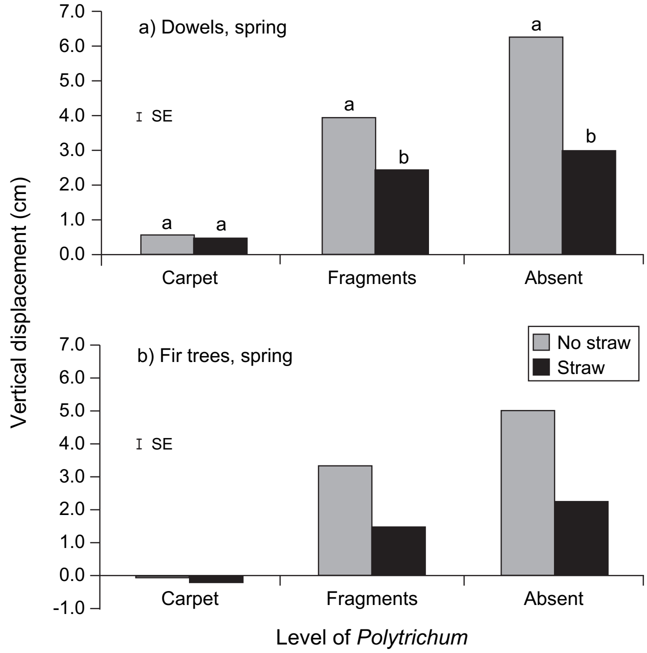

Figure 3. Vertical displacement of dowels and fir trees in spring 2001 (cumulative frost heave from 24 August 2000 to 29 May 2001) due to frost heaving on an abandoned vacuum-harvested bog, Premier St-Laurent, Rivière-du-Loup, Québec. (a) Dowel heave in the spring. $\text{ANOVA}_{\text{Straw}*Polytrichum}$: $df = 2$, $F = 18.16$, $p < 0.0001$. Values followed by different letters are significantly different at $p \leq 0.05$ by the Tukey test for straw effect within each level of *Polytrichum*; Tukey for *Polytrichum* levels when straw is absent: carpet = a, fragments = a, absent = b; Tukey for *Polytrichum* levels when straw is present: carpet = a, fragments = a, absent = a. (b) Fir tree heave in the spring. $\text{ANOVA}_{\text{Straw}*Polytrichum}$, log transformation: $df = 2$, $F = 2.85$, $p = 0.0769$. $\text{ANOVA}_{\text{Straw}}$: $df = 1$, $F = 21.48$, $p < 0.0001$. $\text{ANOVA}_{Polytrichum}$: $df = 2$, $F = 128.60$, $p < 0.0001$. Tukey main effects for *Polytrichum*: carpet = a, fragments = b, absent = c. Tukey main effects for Straw: present = a, absent = b.

not heave in any of the plots covered with straw, whereas in the plots without any straw, the dowels heaved when in bare peat or fragments, but not when planted in the carpet.

Frost heaving results in the fall are the same for the fir seedling, except that on average they heaved more than the dowels (average heaving of dowels = 0.6 cm, average heaving of fir seedlings = 0.82 cm). In some cases, especially on the bare peat, dowels and fir trees heaved completely out of the peat. Because further frost action after the dowels and firs were expulsed was not measured, the values recorded are considered to be minimal values.

Heaving of Dowels and Fir in Spring 2001

By the end of the frost heaving period in spring 2001, virtually all the dowels, except those planted in the *P. strictum* carpet, had heaved (Fig. 3a). As in the fall, a significant interaction was found between straw and *P. strictum*. This is because the dowels planted in bare peat or fragments and covered with straw heaved the same amount: between 2.5 and 3 cm. However, when they were not covered with straw, the dowels planted in the bare peat heaved a lot more than those planted in the fragment treatment.

By the end of the same period, more than half of the fir trees planted in treatments other than the *P. strictum* carpet had heaved so much that their roots were pushed completely or partially out of the peat. None of the fir trees planted in the carpet suffered root exposure; in fact, no heaving was observed in this treatment. There was more heaving in the fragments, and the most heaving was observed in the absence of *P. strictum* where 75% of the seedlings heaved so much that their roots were visible. Fir trees planted in straw heaved half the amount of fir trees planted without straw (Fig. 3b).

Advance of the Thaw Line

On 17 April 2001 the site was visited for the first time at the beginning of the field season. All plots were snow-covered, except four where the snow had partially melted. The peat was still completely frozen. By 25 April 2001 all the snow had melted and the concrete frost had begun to thaw. On 25 April 2001 the average depth to the thaw line was 5.5 cm; that is, there was 5.5 cm of muddy peat overlaying the hard frozen peat. Six days later, on 30 April 2001 the thaw line was on average 7.3 cm below the peat surface. The advance of the thaw line by treatment shows a similar pattern for each date, so only the second date is further discussed.

In the plots covered with straw, the peat thawed more slowly than in those without straw (no significant interaction between *P. strictum* and straw; Straw = 6.2 cm, No straw = 7.8 cm of thawed peat; $\text{ANOVA}_{\text{Straw}}$: $df = 1$, $F = 12.92$, $p = 0.002$). The peat also thawed significantly more slowly in plots covered with *P. strictum* carpet (6.6 cm) and *P. strictum* fragments (6.4 cm) than in plots without any *P. strictum* (8.1 cm; $\text{ANOVA}_{Polytrichum}$: $df = 2$, $F = 5.84$, $p = 0.009$).

Unfrozen Soil Moisture

For this analysis, the two treatments with *P. strictum* carpets were eliminated from the dataset. The peat beneath the carpet was frozen solid, so it was impossible to properly insert the probe and take a measurement.

The peat had a higher unfrozen water content when there was no straw (41%) than when there was straw (32%; $\text{ANOVA}_{\text{Straw}}$: $df = 1$, $F = 14.91$, $p = 0.002$). The water content of the treatments with fragments (32%) tended to be lower than that of the treatments without *P. strictum* (37%; $\text{ANOVA}_{Polytrichum}$: $df = 1$, $F = 4.19$, $p = 0.059$).

Temperature

Temperature data are presented as cumulative temperature curves, where the curve reflects the percent time when temperature is greater than that shown on the y axis. In the fall, during the warmer parts of the day (above 7°C), peat temperature was generally warmest in the bare peat treatment, followed by fragments, straw, and carpet. At night, as the air temperature dropped, the situation was reversed; it was generally warmest under the carpet, followed by straw, fragments, and bare peat (Fig. 4a). This inversion is clearly visible when the temperature is plotted daily, versus time (data not shown).

In the spring, during the warmer parts of the day (above 10°C), peat temperature was generally warmest in the bare peat treatment, followed by the carpet, straw, and fragments (Fig. 4b). As the temperature dropped from 10 to 1°C, it was generally warmer under the carpet, followed by the bare peat, fragments, and straw. At the freezing point, there was very little difference between treatments. For the few values observed below 0°C, it was warmest under the carpet.

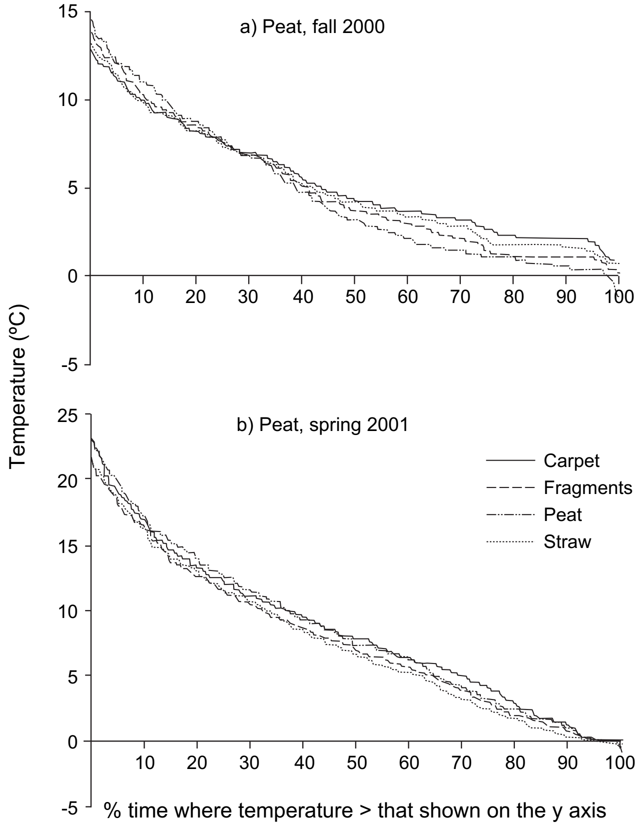

Figure 4. Temperature duration curves for a *Polytrichum* carpet, *Polytrichum* fragments, straw, and bare peat on an abandoned vacuum-harvested bog, Premier St-Laurent, Rivière-du-Loup, Québec. (a) 1.3 cm beneath the peat surface, from 19 to 30 October 2000. (b) 1.3 cm beneath the peat surface, from 26 April 2001 to 11 May 2001. $n = 3$–5 dataloggers per treatment.

Discussion

The Control of Frost Heave on Milled Peatlands

In this study, the carpet of *Polytrichum strictum* moss was the most effective means of reducing frost heaving. In trying to find solutions for the problem of tree seedling frost heaving in nurseries, Jones and Peace (1939) found that covering bare soil with a layer of moss reduced frost heaving of wooden garden labels by 95%, compared to bare soil. We found comparable reduction of 92% for the dowels in the carpets versus those in bare peat. We considered the possible confounding effect of the layer of peat adhering beneath the transplanted carpet by testing the frost heave reduction of the layer of adhering peat (data not shown). Although it reduced frost heaving, it was less efficient than the *P. strictum* carpet or *P. strictum* fragments, and is believed unimportant. Gartner et al. (1986) working in the tussock tundra of the Arctic found that moss and hepatic mats stabilized soil prone to frost heaving. In frost-heaving reduction experiments described by Jones and Peace (1939), the authors found it necessary to cover their moss layer with leaf mold to avoid wind transport, because the moss was apparently not rooted. The species is not mentioned. Wind transport was not a problem for us because we used *P. strictum* moss, which was firmly attached to the peat by its rhizoids. New shoots of *P. strictum* seemed to have the greatest amount of rhizoids that were tightly bound to the underlying peat.

Polytrichum strictum is well known for its ability to stabilize susceptible soils, although this is the first time, to our knowledge, that this has been reported in postharvested peat bogs. Previous studies have reported on the binding effect of *Polytrichum* on volcanic ash, sand, soil, and small rocks, in very windy areas of the Antarctic, and in forests following fire (Leach 1931; Collins 1969; Fenton & Lewis Smith 1982; Maltby et al. 1990).

Straw effectively reduced frost heaving. Whereas there was no frost heaving in any of the treatments with straw in the fall, in the spring there was 2.5–3.0 cm of dowel heave in the bare peat covered with straw and fragments covered with straw treatments. The straw partially decomposed over the winter and lost some of its protective effect. *Polytrichum strictum*, on the other hand, grew, enhancing its protective effect. Field surveys done on a nearby site revealed that 3 years after restoration, only 9% of the site was still covered by straw, and 5 years after restoration, no straw remained on the site at all (Groeneveld 2002). Woods et al. (1978, 1979), working on abandoned coal strip mines, state that the mulch must remain intact enough for tree seedlings to become well established. Straw decomposes very quickly, and unless a plant cover can establish within the first 2 years following restoration, frost heaving may be a problem after the straw is gone. Kohnke and Werkhoven (1963) found that straw mulch, applied on a silt loam soil at 3,362 kg/ha, reduced the number of frost heave cycles in a silt loam soil from 22 to less than 7. Other mulches such as forest litter, bark, wood chips, sawdust, cedar shavings, and wood ashes have been found effective against frost heaving (MacKinney 1929; Smagula & Goltz 1988). These mulches reduce the number of freeze–thaw cycles at the surface of the soil or avoid heaving altogether by delaying the soil freezing until continuous low temperatures set in (Belotelkin 1941; Kohnke & Werkhoven 1963).

The degree of reduction in frost heaving corresponded to the thickness of the ground cover: *P. strictum* carpet was the thickest and therefore provided the greatest reduction in frost heaving. Straw at 3,000 kg/ha was the next best, followed by the fragments spread in a ratio of 1:10. Nonetheless, all three ground covers, the carpet, the fragments, and the straw, reduced frost heaving to varying degrees. At night, these mulches reduced heat loss to the atmosphere, reducing the potential for ice crystal formation. During the daytime, the effect was reversed: temperatures were cooler under the mulches and warmer on the bare peat. This lowered daytime temperature means that ground frozen during the night was less likely to thaw during the day. It follows that soil, which remains frozen during the day, does not heave at night, because there is no liquid water available for needle ice formation (Graber 1971). In that respect, soil moisture is one of the main controls on frost heaving. A wet soil has the potential to heave, a dry soil does not (Higashi 1958; Grant & Saini 1973; Matsuoka 1996). In this study, soils covered with fragments and/or straw had lower moisture content than the bare peat in the spring, most likely alleviating the frost heaving phenomenon by thawing more slowly, thus retaining their water in ice form.

Once the snow cover had melted, the peat quickly began to thaw, averaging 0.36 cm per day in the bare peat. When the water in peat melts, the thawing process is promoted because wet peat conducts heat better than frozen peat (Nakano & Brown 1972). Rydén and Kostov (1980) found that wet peat in depressions thawed more quickly than elevated well-drained peat and attributed this difference to the increased thermal conductivity of wet peat. As the thaw deepens, the volume of water available for needle ice formation increases. Areas with a deeper thaw line, such as the bare peat surfaces, are therefore more susceptible to heaving. Graber (1971) noted that as the soil on an old field began to thaw from the surface downward, the concrete frost acted as a drainage barrier, holding the melt water at or near the surface. The result was severe frost heaving and extensive plant damage, as was observed in plots with bare peat in this experiment.

Soils that thaw later are less prone to frost heaving because in the spring the night temperatures quickly rise and stay above freezing. As long as the peat had some sort of covering, be it moss or straw, the thawing process was slowed. The relatively quick thaw on the bare soil at a time when night temperatures dipped below freezing made them susceptible to frost heaving. In this study, the last spring night that soil temperature dipped below freezing was 30 April 2001. So plots that thawed after this time (e.g., those covered with straw and/or moss) were not at risk for frost heaving.

Dowels and tree seedlings had similar heaving patterns; this had also been found in other studies (Decker & Ronningen 1957; Portz 1967). The dowels were more readily obtainable and easier to install and monitor for frost heaving than fir trees. The dowels are therefore a good biological model for frost heaving and the study of nurse-plant effects.

Frost heaving has long been recognized as a hazard to young tree seedlings (Haasis 1923; Buell et al. 1971; Gill & Marks 1991). There is no doubt that the reduction in frost heaving of the peat substrate was a major factor influencing the health and survival of fir trees in this study. Trees which have suffered frost heaving damage to their roots are more susceptible to drought damage in the summer (Larson 1960). Trees growing in the *P. strictum* carpet, *P. strictum* fragments, and straw mulch had a double benefit; they suffered less frost heaving damage over the winter and were offered a more moist microclimate in the summer (Groeneveld 2002).

Implications for Disturbed Ecosystems

In this study, we have clearly demonstrated that the moss *P. strictum* can reduce frost heaving on a highly disturbed ecosystem. The *Polytrichum* genus is a common taxon in many boreal ecosystems. As such, other *Polytrichum* species may be effective nurse-plants in other ecosystems where soil stability and plant regeneration are problematic, such as sand pits and burned or cut forests. The role of mosses at the level of ecosystem functioning should not be underestimated.

For peatland restoration on sites where peat instability does not appear problematic, straw is the best mulch because it confers the same protection as *P. strictum*, at least immediately after application. However, on those sites where instability is a problem, straw alone is not the best option. It can easily blow away in windswept peat fields, and its effect is short term due to rapid decomposition. In these cases, *P. strictum* becomes an interesting addition to restoration techniques. Straw mulch is still considered necessary because it takes at least two growing seasons for *P. strictum* to reach an appreciable size, and the mulch enhances *P. strictum*'s establishment. Experiments have shown that it is relatively easy to quickly establish a vigorous *P. strictum* carpet on a postharvested bog, using the North American approach to peatland restoration (Rochefort et al. 2003).

The extent of competition between *P. strictum* and its benefactor plants, especially *Sphagnum,* remains unclear at this time. An interesting question is, "Under what conditions does *P. strictum* enhance the establishment of *Sphagnum*, and under what conditions does competition negate the positive facilitation?" Further research is needed.

Acknowledgments

This study was funded by the Natural Sciences and Engineering Research Council of Canada and by industrial partners who are members of the Canadian Sphagnum Peat Moss Association. We extend our deepest thanks to the research assistants who participated in data collection during the study, particularly Ariane Massé.

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