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Abstract

Winter roads across subarctic peatlands are increasingly being used to access remote communities and resource development camps, yet relatively little is known on their ability to recover after abandonment. We evaluated the natural recovery of winter roads abandoned within 7 years on peatlands in the Hudson Bay Lowland, Canada. We sampled 5 winter roads of increasing age of abandonment and compared surface elevation, microtopography, active layer thickness, species cover, diversity, and composition between winter road clearances and adjacent undisturbed peatland. No differences in surface elevation and hummock-hollow microtopography were detected between road clearances and adjacent peatlands, but clearances had significantly thinner active layer, which persisted at least 7 years after abandonment. The cover of lichens, bryophytes, and vascular plants returned within 5 years to similar levels as in undisturbed peatlands, although species richness per quadrat remained lower and species composition differed. The limited recovery of black spruce on these peatlands and their slow growth indicates that the full recovery of vegetation structure on these road clearances will take decades. Future research should focus on the restoration of a *Sphagnum* carpet and on the interactions between a shallower active layer and the revegetation of abandoned winter roads.

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Introduction

Access over land is required to transport heavy equipment and supplies to remote communities, resource extraction camps, and exploration sites across the high boreal, subarctic, and Low Arctic regions (e.g. Far North Science Advisory Panel, 2010). Where no network of all-season roads exists, winter access has been favored since the 1960s to limit the damage to terrestrial ecosystems by heavy-axled vehicles, especially in regions with permafrost (Bliss and Wein, 1972; Adam and Hernandez, 1977). Winter access in these regions can be either over winter trails (e.g. seismic lines) or on winter roads (Adam, 1978; INAC, 2010). Winter trails are typically single-pass trails by convoys of tracked heavy-axled vehicles. Natural frost penetration in the ground is relied upon to support their weight and there is no prior surface preparation. In contrast, winter roads are built for repeat winter traffic by heavy-axled wheeled vehicles, including haul trucks. All woody vegetation is first cleared, and each winter, a load-bearing road bed is prepared over the ground with packed snow or ice.

Much of the research on impacts has concentrated on winter trails. They cause mechanical damage to the standing vegetation (Bliss and Wein, 1972; Adam and Hernandez, 1977; Felix and Raynolds, 1989a), and if the depth of frozen soil is insufficient, they disturb or compact the surface organic layers (Bliss and Wein, 1972; Felix and Raynolds, 1989b). This organic matter acts as a key insulator for the soil (Haag and Bliss, 1974), so in regions with permafrost, its damage leads to increased depths of the active layer (Bliss and Wein, 1972; Hernandez, 1973; Haag and Bliss, 1974) and potentially to thermokarst erosion (Forbes et al., 2001). If surface organic layers remain intact, the active layer on winter trails is generally not affected (Kemper and Macdonald, 2009a, 2009b). Upland environments are more resistant to damage from winter trails but show delayed recovery once disturbed, whereas lowlands are more sensitive to initial disturbances but recover faster, unless disturbance is excessive (Bliss and Wein, 1972; Hernandez, 1973; Emers et al., 1995; Kemper and Macdonald, 2009a, 2009b; Jorgenson et al., 2010).

For winter roads, almost no cover of live vascular plants, mosses or lichens remains in subsequent growing seasons, especially along the center of the road clearances (Bliss and Wein, 1972; Hernandez, 1973; Adam and Hernandez, 1977). The loss of vegetation increases the active layer thickness in regions with permafrost (Adam and Hernandez, 1977), but, as with winter trails, this effect is exacerbated if surface organic layers are disturbed to reveal mineral soils, which can lead to ground subsidence (Haag and Bliss, 1974). In contrast to winter trails, limited research exists on the effects of winter roads on upland versus lowland ecosystems, and none report longer-term impacts beyond 2 years (Adam and Hernandez, 1977). This is surprising considering that winter roads form linear disturbances that can make up a large fraction of the area impacted by remote resource exploration and extraction.

The Hudson Bay Lowland (HBL) is a vast undisturbed expanse of subarctic to Low Arctic peatlands in north-central Canada, covering 373,700 km^2 southwest of James Bay and Hudson Bay, making it the third largest wetland in the world (Abraham and Keddy, 2005). Much of the region has continuous to discontinuous permafrost (Riley, 2011). Recent discoveries of important mineral deposits in the region for diamonds, base metals, and precious metals have led to the opening of one mine and intense exploration across this region (Far North Science Advisory Panel, 2010). All-season roads cannot cross these peatlands without great environmental damage or cost, so industries as well as First Nation communities rely on a network of winter roads to transport heavy equipment and supplies. Subsidence has been identified as a potential problem for winter roads built over peatlands (INAC, 2010), which raises questions on the potential for ecological impacts of winter roads in the HBL, but little research has been published on this subject.

The purpose of this study was to determine how peatlands in the HBL naturally recover from damage caused by winter roads over a sequence of roads of increasing age of abandonment. Specifically, we were interested in whether winter road clearances showed signs of subsidence or increased active layer, as predicted from previous research, and how the cover, diversity, and species composition of lichens, bryophytes, and vascular plants returned to road clearances following their abandonment.

TABLE 1

Use and abandonment of winter roads under study near the Victor Mine in the Hudson Bay Lowland. Microtopography and vegetation surveys were conducted in June–July 2008, while active layer thicknesses were examined in August 2010.

Road	First use	Last use	Use
New	winter 2007	ongoing	heavy traffic with thousands of loads
Esker	winter 2006	winter 2007	light traffic with ∼100 trucks/winter
Entry	winter 2006	winter 2006	heavy traffic
South	winter 2003	winter 2005	light traffic for drill rig access
Old	winter 2002?	winter 2003	light traffic for drill rig access

Methods

The study was conducted in the Hudson Bay Lowland around the De Beers Canada Victor Mine (52°48′N, 83°54′W; 83 m elevation), 110 km east of James Bay, Ontario. The region consists of a vast and flat limestone plain, overlain largely by marine silts and capped by ∼2 m of peat. Peatlands cover the entire landscape, with less than 2% drained uplands on old beach ridges, limestone outcrops, and along slopes of river valleys. Peatlands vary from fens that are rich in carbonates to mineral-poor bogs (Sjörs, 1963; Riley, 2011). Pools are often present, especially in fens, where diffuse flark-string sequences can be found. The dominant vegetation consists of sparse and stunted black spruce (*Picea mariana*) and tamarack (*Larix laricina*), ericaceous shrubs, sedges (*Carex* and *Eriophorum*), bryophytes, especially *Sphagnum* species, and lichens (*Cladina* and *Cladonia*). Permafrost is discontinuous and underlies most peatlands around Victor Mine (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 1244 growing degree days above 5 °C (Environment Canada, 2010). Mean annual precipitation is 700 mm, over half of which falls from June to September during the growing season.

The Victor Mine is an open pit diamond mine that began full operation in 2008, after almost a decade of advanced exploration, feasibility and impact studies, and construction activities. Land access is restricted to winter roads, so several abandoned and current winter roads surround the mine site. Winter roads are usually constructed in mid-December to mid-January. Once 30–60 cm of snow lies on the peatlands, the snow is packed using snowmobiles to reduce the insulation of the snow and allow deep freezing of the peat. When 15 to 25 cm of frost is in the peat, a light, wide-track bulldozer is used to pack the snow further and to drag heavy tires or steel drags back and forth at slow speed. Larger trees on the road clearance are cut by hand or 'shear-bladed' at ground level with a sharp-bladed bulldozer or snow-cat after the peat freezes, leaving the tree roots intact in the ground. When the frost depth in the road clearance increases enough to support rubber-tired equipment, a road grader is used to further smooth the surface. It either scrapes off excess snow to improve ground frost penetration or pulls snow in from the sides of the road to increase the thickness of the packed snow. Once the road surface is solid and smooth, trucks water and saturate the surface snow and thereby create a 10 to 15 cm load-bearing ice cap on top of the packed snow. This ice cap is not intended to extend to the peat surface, which otherwise would allow sunlight to penetrate and melt the road from the bottom up. Peatland pools are avoided where possible.

Five winter roads were sampled from 20 June to 20 July 2008 for all parameters except depth of the active layer (Table 1). They ranged in age from the New road in current use to the Old road, abandoned in 2003 a full 5 years prior to the study. The roads were sampled within ∼4 km of the Victor Mine and were 0.2 to 6 km apart from each other. On each road clearance, three sites were selected at random, separated by 50–200 m. At each site, two 19-m transects were sampled, one across the width of the winter road clearance and one in the adjacent undamaged peatlands. As such, the study had a factorial design with road, site, and transects as the main factors.

Three water samples were collected at each site from the hollows or from a dug hole. In the lab, pH was measured using an Accumet Basic AB15 pH meter, and electrical conductivity was measured using an Orion 4-Star pH/conductivity portable meter. Conductivity was corrected for hydrogen ions (Strong, 1980).

Surface height was sampled at every 0.5 m along each transect using a laser level and a meter stick. The depth to the water table was determined on each pair of transects in water-filled hollows. If no water was visible, a hole was dug and left to fill. Surface height was then expressed as a height relative to the mean water table over a pair of transects. The mean surface height and standard deviation of surface height were then calculated on each transect for a measure of ground surface subsidence and variation in microtopography, respectively.

Vegetation surveys were conducted along each transect by placing a 0.25 m^2 square quadrat every 1.5 m for a total of 15 quadrats per transect. Within each quadrat, the percent cover of total lichens, total bryophytes, and total vascular plants was estimated visually. All lichens, bryophytes, and vascular plants were then identified to species and recorded. Nomenclature follows the Integrated Taxonomic Information System (http://www.itis.gov).

Species richness of lichens, bryophytes, and vascular plants was determined for each quadrat, then averaged per transect. Species richness across entire transects was also determined for each of these plant groups. Simpson's diversity index (1– D; Magurran, 2004) was calculated for each plant group based on the quadrat data. The frequency of each species in quadrats was tallied per transect and then used for species composition analyses.

Sites were revisited on 13–15 August 2010 to measure the depth of the active layer, which had not been measured in 2008. The New road remained in use each winter, while the Old, Esker, and Entry roads had remained abandoned. The South road sampling sites were severely disturbed and were not resampled. Active layer depth was determined at 2-m intervals along transects on the road clearance and in the undisturbed peatland, by pushing a 1.7 m × 2 cm diameter metal rod into the ground until it hit solid frost. Active layer depth was expressed as the depth below the mean ground surface as determined from a laser level and a meter stick.

Analyses of variance were used to test for the effects of road and transect and their interaction using a common ANOVA model, in which road and transect were set as fixed factors and site was set as a random factor to account for the pairing of transects between road clearances and adjacent undisturbed peatland. Only the interaction between road and transect was included. Using this model, analyses were completed separately for mean surface height, standard deviation of surface height, active layer depth and cover, richness per quadrat, richness per transect, and Simpson's index of lichens, bryophytes, and vascular plants. Plots of residuals versus predicted values were examined to verify assumptions, and variables were transformed if necessary. For parameters with significant interactions in ANOVA, protected LSD *post hoc* tests were performed for each road separately to compare road clearances with adjacent undisturbed peatland. These analyses were conducted using Statistica 10.

Differences in species composition between roads and between transects were analyzed using PERMANOVA+ (PRIMER-E, 2008). This technique provides a randomization-based analysis akin to MANOVA for species assemblage data. A resemblance matrix was first calculated on raw assemblage data using the Bray-Curtis similarity measure. Differences in species composition were then tested using the same model as for the ANOVA, through 10,000 random permutations. This analysis was followed by a SIMPER analysis (PRIMER-E, 2008) to determine which species differ between road clearances and adjacent undisturbed peatlands. For all analyses, significance was established at $\alpha = 0.10$ because of concerns of committing Type II errors.

Results

The sampled peatlands occurred along a gradient of water pH and corrected conductivity (Appendix 1). The pH varied from acid (pH 4) to near circumneutral conditions. Most peatland sites had very low conductivity ($<100\ \mu S\ cm^{-1}$), with the exception of one site along the South road with elevated conductivity.

Mean height of the surface relative to the water table did not differ between winter roads and undisturbed peatlands, nor among roads, and no interaction was present (Table 2), indicating that no subsidence was detected. Although not significantly different, average surface height relative to mean water table was slightly higher on winter roads as compared to undisturbed peatland (mean ± SE: 12.5 ± 4.1 on roads; 8.5 ± 3.1 cm off roads, $n = 15$ each). When standard deviation of surface height was considered, again, no significant difference existed between the winter road surfaces and the adjacent undisturbed peatlands and again no significant interaction was present, therefore the winter roads did not appear to affect the variability in the hummock-hollow topography, at least at the transect interval of 0.5 m used in this study.

TABLE 2

Results of ANOVA testing for the effect of road (time since abandonment), site (random factor), transect (road clearance versus undisturbed peatland), and the road by transect interaction on mean elevation and standard deviation of elevation across transects in summer 2008 and thickness of the active layer in summer 2010. Elevation was square-root transformed to meet the assumptions of the ANOVA. All effects with $P < 0.10$ are shown in bold.

Variable	Source	df	MS	F	P
elevation	road	4	14.2	2.1	0.119
	site	2	0.5	0.1	0.924
	transect	1	2.5	0.4	0.545
	ro × tr	4	11.3	1.7	0.198
	error	18	6.7		
SD elevation	road	4	0.69	0.4	0.820
	site	2	3.64	2.0	0.163
	transect	1	1.29	0.7	0.410
	ro × tr	4	1.56	0.9	0.507
	error	18	1.81		
active layer	road	3	1484	13.1	**<0.001**
	site	2	36	0.3	0.735
	transect	1	13747	121.5	**<0.001**
	ro × tr	3	1054	9.3	**0.001**
	error	14	113		

When we returned in late summer 2010 to measure the depth of the active layer, the frost was significantly deeper in undisturbed peatland as compared to winter road clearances (Table 2; Fig. 1). The active layer in undisturbed peatlands was consistently 100–150 cm deep over all roads, while on road clearances the frost was significantly closer to the surface. There was also a strong interaction ($P = 0.001$); although all road clearances had thinner active layers than in adjacent natural peatland (*post hoc* LSD, $P < 0.05$), the road clearance of the New road had a shallow active layer of only 30–40 cm, whereas the other road clearances had deeper active layers, and this effect increased with the age of the road. The Old road still had a shallower active layer than the adjacent undisturbed peatland (*post hoc* LSD, $P = 0.047$), although it had been abandoned in 2003, 7 years before these measures were taken.

Over all transects on winter road clearances and in adjacent undisturbed peatlands, 70 species of lichens, bryophytes, and vascular plants were encountered in 2008. The most frequent species included black spruce (*Picea mariana*), ericaceaous shrubs (*Chamaedaphne calyculata*, *Vaccinium oxycoccus*, *Kalmia polifolia*, *Ledum groenlandicum*, and *Andromeda polifolia*), herbs (*Maianthemum trifolium*, *Rubus chamaemorus*, *Drosera rotundifolia*, and *Eriophorum vaginatum*), bryophytes (*Sphagnum angustifolium*, *Sphagnum fuscum*, *Dicranum scoparium*, and *Mylia anomala*) and reindeer lichens (*Cladina rangiferina* and *Cladina stellaris*; Appendix 2).

Less cover of bryophytes and vascular plants occurred on abandoned winter road clearances, but lichens cover was not different (Table 3; Fig. 2). A significant interaction occurred for bry-

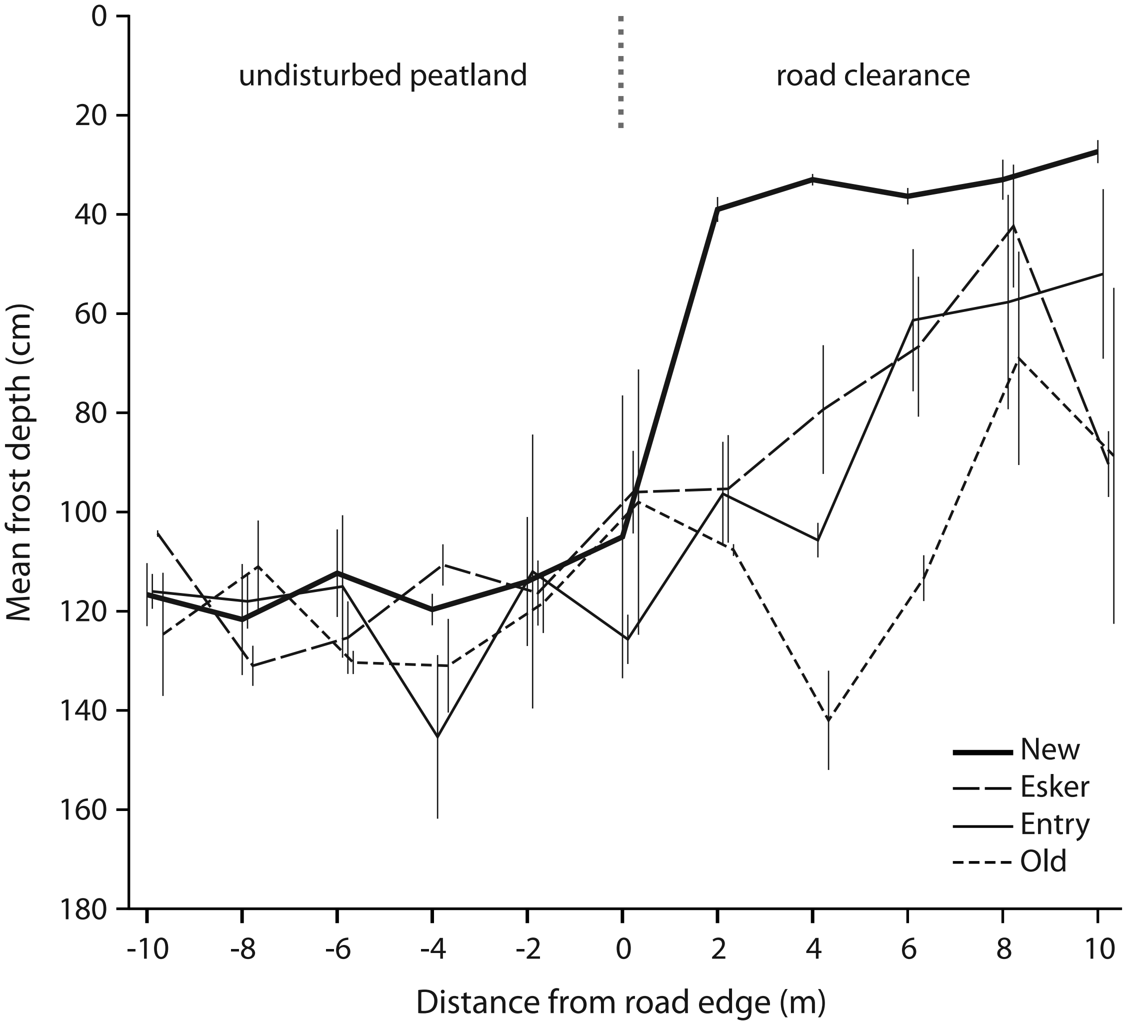

FIGURE 1. Active layer thickness along transects crossing road clearances and into the adjacent peatland for four roads sampled in mid-August 2010 (mean ± SE; $n = 3$). Transects in natural peatlands were immediately adjacent and continuous with transects across winter road clearances.

ophytes (P = 0.030) and a borderline interaction occurred with vascular plants ($P = 0.104$), which showed that differences in cover between winter road clearances and undisturbed peatlands disappeared on older roads (Fig. 2, Part b), especially along the South and Old roads.

Undisturbed peatlands had significantly more species per quadrat for lichens, bryophytes, and especially for vascular plants as compared to the winter road surfaces (Table 3, Fig. 3), although a significant interaction for vascular plants showed that their species richness per quadrat began to recover on older roads (Fig. 3, Part c). When species richness was considered across entire transects, there was no difference between the road clearances and the undisturbed peatlands for lichens, bryophytes, or vascular plants, and no interaction was present (Table 3; mean ± SE: lichens = 4.0 ± 0.4; bryophytes = 7.5 ± 0.4; vascular plants = 13.1 ± 0.5). The differences in species richness therefore occurred at the fine scale 50 × 50 cm quadrat level and not at the coarser scale 10 m transect level. The Simpson's index showed that species assemblages had similar dominance relationships between winter roads and the adjacent undisturbed peatland for lichens, bryophytes, and vascular plants, with no interactions (Table 3). Overall, distributions of assemblages were even, especially for bryophytes and vascular plants ($1-D$, mean ± SE: lichens = 0.63 ± 0.05; bryophytes = 0.80 ± 0.02; vascular plants = 0.90 ± 0.00).

From the PERMANOVA analysis, species composition differed significantly between the roads and the adjacent undisturbed peatland (pseudo-$F_{1,18} = 3.22$, $P = 0.003$) and also among the winter roads (pseudo-$F_{4,18} = 4.05$, $P < 0.001$), but no interaction was present (pseudo-$F_{4,20} = 0.77$, $P = 0.80$), meaning that differences in species composition between winter road clearances and adjacent peatlands did not depend on its age of abandonment. The SIMPER analysis showed that quadrats on the winter roads had more frequent *Maianthemum trifoliata*, *Dicranum scoparium*, *Andromeda polifolia*, and *Eriophorum vaginatum* than in undisturbed peatlands, in order of decreasing contribution to the Bray-Curtis distance (Appendix 2), and less frequent *Cladina stellaris*, *Sphagnum angustifolium*, *Sphagnum fuscum*, *Cladina rangiferina*, *Drosera rotundifolia*, *Kalmia polifolia*, *Picea mariana*, *Ledum groenlandicum*, *Rubus chamaemorus*, *Mylia anomala*, and *Vaccinium oxycoccus*.

TABLE 3

Results of ANOVA testing for the effect of road (time since abandonment), site (random factor), transect (road clearance versus undisturbed peatland), and the road by transect interaction on cover, species richness per quadrat, species richness per transect and Simpson's diversity (1– *D*) per transect for lichens, bryophytes, and vascular plants sampled along winter roads in summer 2008. Lichen cover was square-root transformed to meet the assumptions of the ANOVA. All effects with $P < 0.10$ are shown in bold.

			cover			richness/quadrat			richness/transect			Simpson's diversity		
Group	Source	df	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
lichen	road	4	1.51	6.0	**0.003**	1.55	23.7	**<0.001**	11.28	2.6	**0.072**	0.177	3.4	0.032
	site	2	0.14	0.5	0.590	2.64	40.3	**<0.001**	3.63	0.8	0.452	0.204	3.9	0.039
	transect	1	0.28	1.1	0.307	0.36	5.4	**0.032**	5.63	1.3	0.271	0.093	1.8	0.200
	ro × tr	4	0.07	0.3	0.899	0.10	1.5	0.253	1.55	0.4	0.838	0.060	1.1	0.370
	error	18	0.25			0.07			4.37			0.053		
bryophyte	road	4	1812	6.3	**0.003**	3.80	4.9	**0.007**	9.92	2.2	0.106	1.6E–02	1.7	0.184
	site	2	434	1.5	0.248	0.66	0.8	0.444	1.30	0.3	0.750	6.4E-03	0.7	0.504
	transect	1	5626	19.6	**<0.001**	2.82	3.6	**0.072**	0.30	0.1	0.798	9.1E-07	0.0	0.992
	ro × tr	4	999	3.5	**0.030**	0.32	0.4	0.793	0.72	0.2	0.955	9.1E-04	0.1	0.981
	error	18	286			0.77			4.45			9.0E-03		
vascular	road	4	314	12.0	**<0.001**	3.96	5.4	**0.005**	6.22	0.8	0.528	4.6E-05	0.2	0.956
	site	2	2	0.1	0.931	3.69	5.0	**0.018**	10.30	1.4	0.281	8.0E-04	2.8	**0.087**
	transect	1	660	25.3	**<0.001**	16.63	22.7	**<0.001**	0.83	0.1	0.744	3.7E-04	1.3	0.270
	ro × tr	4	59	2.3	**0.104**	2.37	3.2	**0.036**	12.58	1.7	0.202	4.3E-04	1.5	0.249
	error	18	26			0.73			7.56			2.9E-04		

Discussion

Current Canadian guidelines for winter road construction state that peatlands should be avoided because of concerns of road bed instability and subsidence (INAC, 2010). Clearly, our results show that the techniques used to build these winter roads on peatlands were successful in avoiding ground subsidence. We did not see any other sign of rutting on the roads examined. The peats must have been sufficiently frozen and the snow and ice cap must have been sufficiently thick to bear the weight of road construction equipment and subsequent traffic by heavy-axled, wheeled vehicles. Neither was there any difference in microtopographic variation between winter roads and undisturbed peatlands. Microhabitats related to the hummock-hollow topography in peatlands (e.g., Andrus et al., 1983) appear to be retained. We expected to see less hummock-hollow microtopography on the winter roads, since some tall hummocks are sheared off during road preparation and plant debris often ends up in hollows, as we observed on the New road constructed the previous winter. Changes in hummock-hollow microtopography may exist at smaller scales of measurement than at the 50 cm interval measured in this study.

The active layer was shallower over the road clearances, and this difference has persisted at least 7 growing seasons after the abandonment of the winter road, as in the case of the Old road. The New road only thawed to a depth of 30–40 cm, despite a warmer than normal growing season in 2010. We initially expected that winter roads over subarctic peatlands would have a similar or thicker active layer over the road clearance as compared to adjacent areas, because of decreased albedo over the bare peat and increased net radiation (Haag and Bliss, 1974). Previous studies of winter roads have shown this effect over lowlands or uplands with shallow peat in the Low Arctic and subarctic (Hernandez, 1973; Haag and Bliss, 1974; Adam and Hernandez, 1977). Low arctic winter trails also have similar or thicker active layers over uplands or lowlands as compared to adjacent undisturbed sites (Felix et al., 1992; Emers et al., 1995; Kemper and Macdonald, 2009b).

The thinner active layer observed on the road clearances in our study could be a lingering after-effect of a winter road's active period, in which case winter road beds are still slowly thawing, at least 7 years after their abandonment. Alternatively, the slow recovery of vegetative cover on road clearances and especially the limited recovery of black spruce may change their energy balance. Subarctic vegetation with krummholz black spruce and evergreen ericaceous shrubs traps more snow, and that snow remains less dense than in open wind-swept areas such as the cleared road right-of-way (Arseneault and Payette, 1992; Rouse et al., 2000). This would increase the insulation in undisturbed peatlands as compared to the road clearance. Shallower snow cover is related to decreased soil temperature and a thinner active layer (Annersten, 1966; Nicholson and Granberg, 1973; Zhang, 2005), which is exactly the principle of creating a winter road bed. During the summer, the open nature of the road clearances would also allow more direct irradiation and convective exchanges with the ground surface that promote the drying of surface peat (Tyrtikov, 1973). Dry surface peat has low thermal conductivity and would also act as a good insulation (Tyrtikov, 1973), impeding thaw under winter road clearances. If a thinner active layer translates to lower temperatures in the rooting zone, the growth of roots and rhizomes of vascular plants along the road clearances will be impeded, affecting their recovery.

Cover of total lichens, bryophytes, and vascular plants returned to levels similar to undisturbed peatlands 5 years after abandonment, even though vegetative structure is less complex, richness is lower, and composition has changed. It is unclear to what extent different species began to recover after the initial disturbance, or only after the final abandonment. Dwarf shrubs, herbaceous plants, bryophytes, and perhaps lichens could begin to recover shortly after the initial disturbance. Many peatland vascular plants are rhizoma-

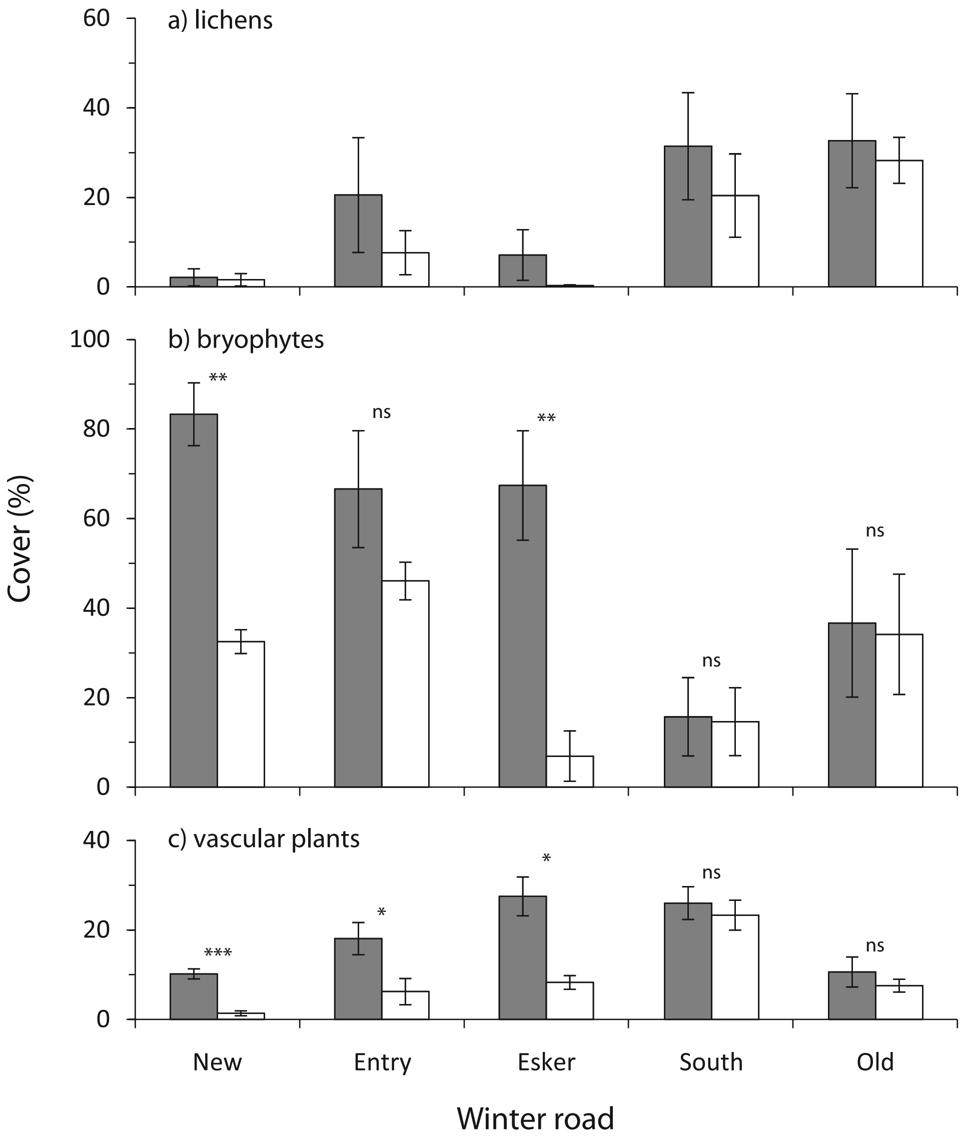

FIGURE 2. Mean cover of lichens, bryophytes and vascular plants on winter road clearances (shaded) and in adjacent natural peatland (unshaded) in the Hudson Bay Lowland (± SE, n = 3). Roads are ordered by increasing age of abandonment. For lichens, no significant road × transect interaction was present (Table 3). For bryophytes and vascular plants which had significant road × transect interactions in the ANOVA, the results of protected LSD *post hoc* tests are shown comparing road clearances with adjacent undisturbed peatland within a single road (ns: not significant; *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$).

tous, and their belowground biomass of rhizomes and roots greatly surpasses aboveground biomass, often by a more than an order of magnitude (Wallén, 1986; Sjörs, 1991). Since only the aboveground biomass is cut on winter roads, vegetative recovery from underground parts gives them the potential to recover rapidly. Some rhizomatous vascular plants were even more frequent on the roads than off the roads, such as *Maianthemum trifolium* and *Andromeda polifolia*. Another vascular plant, *Eriophorum vaginatum*, also increased in frequency on winter roads relative to undisturbed peatlands, but it is tussock-forming and not rhizomatous. It is a good disperser and readily establishes from seed (Campbell and Rochefort, 2003; Campbell et al., 2003), which suggests that this species at least was recruited from seed on the winter road clearances. Tree species were less frequent on winter roads as expected because they were cut, and black spruce remained less frequent in quadrats on the road clearances as in adjacent undisturbed peatland, even on the older roads, where it is about a third less frequent on the road clearances. Black spruce also grows very slowly on peatlands in the HBL, with average stem radial growth rates of 0.2 mm yr^{-1} (Talarico and Campbell, unpublished data), so the return of the krummholz vegetation structure on winter roads is expected to take several decades.

Most peatland bryophytes and fruticose lichens regenerate well from fragments if environmental conditions are suitable (Rochefort, 2000; Cobbaert et al., 2004; Roturier et al., 2007). During winter road construction, the clearing and dragging of the surface spreads bryophyte or lichen fragments along the road surface. If not buried, these fragments could therefore allow the recovery of bryophytes and lichens along winter road clearances. In block-cut peatlands in southern Québec and New Brunswick that are drained and much more severely disturbed, *Sphagnum* re-establishes after abandonment without human intervention, unless conditions are too dry (Poulin et al., 2005). However, many cut hummocks on the road clearances were quite dry in mid-summer, potentially limiting their recolonization by bryophytes at least. *Sphagnum* species were generally less frequent on winter road clearances, perhaps as a result of drier surface conditions. *Sphagnum* species are primarily responsible for peat accumulation in peatlands (Rochefort, 2000), so it is important to ensure their recovery.

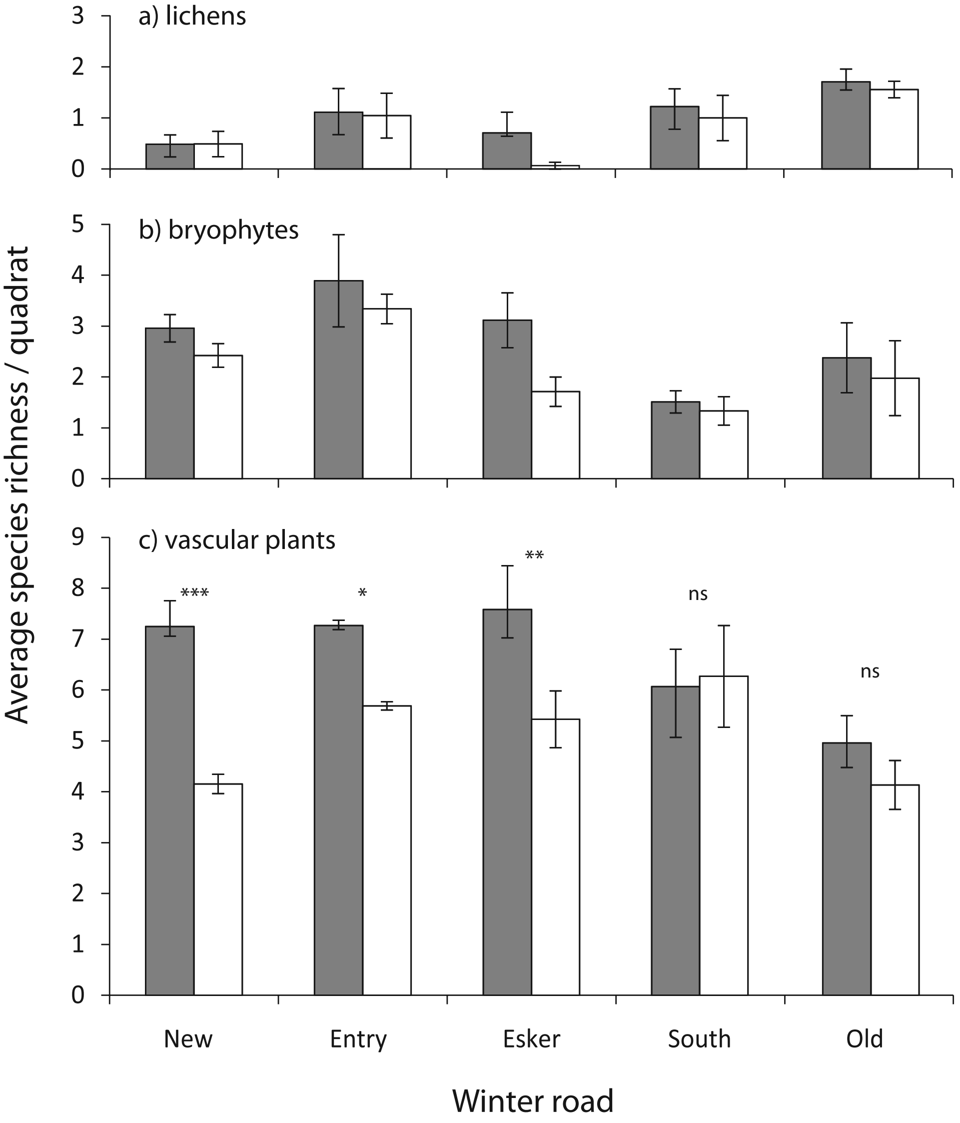

FIGURE 3. Average species richness of lichens, bryophytes, and lichens per 0.25 m^2 quadrat on winter road clearances and in adjacent natural peatlands (± SE, $n = 3$). Roads are ordered by increasing age of abandonment. For lichens and bryophytes, no significant road × transect interaction was present (Table 3). For vascular plants, which had significant road × transect interactions in the ANOVA, the results of protected LSD *post hoc* tests are shown to compare road clearances with adjacent undisturbed peatland within a single road (ns: not significant; *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$).

In conclusion, our results suggest that vegetation on winter road clearances over peatlands recovers in terms of cover within approximately 5 years of abandonment, but species richness and composition take longer time to recover. The structure of the vegetation, characterized by stunted black spruce krummholz, is also slow to return. This lack of vegetation structure may cause the thinner active layer over road clearances. The slow return of *Sphagnum* may also hamper the recovery of peatlands because of its keystone role in peat formation. Consideration should be given to replanting black spruce on winter road clearances to improve vegetation structure. Approaches for active restoration of a sphagnum carpet should be evaluated using recognized techniques of fragment spreading, surface protection, and light fertilization (Rochefort, 2000). Future research should also focus on the interactions between a shallower active layer and the revegetation of these abandoned winter road clearances.

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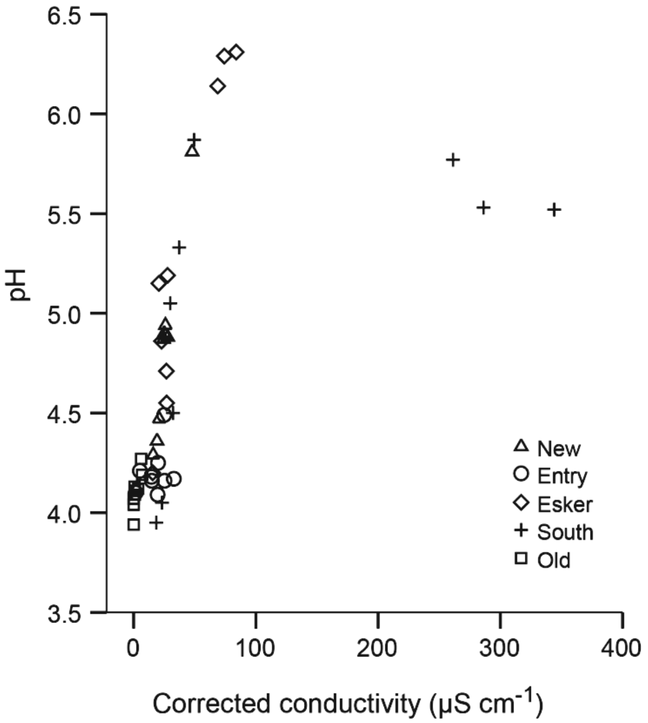

Appendix 1. pH and electrical conductivity for three water samples at each site along the winter roads. Conductivity is corrected for hydrogen ions.

Appendix 2. Average frequency of species in quadrats on winter road clearances as compared to adjacent undisturbed peatland (*n* = 15 pairs of transects) and their contribution to the Bray Curtis difference, as determined from the SIMPER analysis. Only species that contribute to >0.05% of the Bray Curtis distance are shown. Individual species below were not evaluated for significant differences; rather, the entire composition was evaluated for differences using PERMANOVA+ analyses, as reported in the main text. Nomenclature follows the Integrated Taxonomic Information System (http://www.itis.gov).

	Average number of quadrats/transect		
Species	Undisturbed peatland	Abandoned winter roads	Contribution (%)
Lichens			
Cladina mitis	1.6	1.6	1.4
Cladina rangiferina	5.7	4.0	4.4
Cladina stellaris	5.1	4.1	4.9
Cladonia gracilis elongata	0.5	0.5	0.6
Cladonia pyxidata	0.5	0.5	0.8
Foliose lichen species	0.5	0.7	0.9
Icmadophila ericetorum	0.6	0.2	0.6
Bryophytes			
Cladopodiella fuitans	1.8	1.2	1.5
Dicranum scoparium	3.1	4.3	3.7
Drepanocladus fluitans	1.3	1.2	1.7
Mylia anomala	7.2	4.7	3.7
Polytrichum strictum	0.4	1.1	1.1
Sphagnum angustifolium	7.4	5.9	4.7
Sphagnum capillifolium	0.5	0.1	0.6
Sphagnum cuspidatum	0.5	0.3	0.6
Sphagnum fallax	0.8	0.7	1.1
Sphagnum fuscum	10.9	8.3	4.7
Sphagnum magellanicum	2.5	0.8	2.2
Sphagnum majus	0.9	0.4	1.0
Sphagnum rubellum	1.1	0.7	1.3
Sphagnum russowii	2.5	1.8	2.4
Vascular plants			
Andromeda polifolia	2.9	3.8	3.2
Carex aquatilis	0.7	0.6	1.1
Carex limosa	1.5	2.2	2.3
Carex pauciflora	0.7	0.3	0.8
Chamaedaphne calyculata	14.0	13.1	1.8
Drosera rotundifolia	8.9	3.9	4.7
Equisetum fluvatile	1.0	0.8	1.3
Equisetum palustre	1.3	0.5	1.4
Eriophorum angustifolium	0.9	0.1	0.8
Eriophorum vaginatum	2.2	2.9	3.1
Geocaulon lividum	1.9	1.3	2.1
Kalmia angustifolia	0.5	0.4	0.7
Kalmia polifolia	10.1	6.7	4.2
Larix laricina	0.7	0.3	0.7
Ledum groenlandium	9.2	6.4	3.9
Maianthemum trifoliata	9.3	9.9	6.0
Menyanthes trifoliata	0.4	0.6	0.7
Picea mariana	6.9	2.3	4.2
Rubus chamaemorus	9.6	7.2	3.7
Sarracenia purpurea	0.8	0.7	0.9
Trichophorum caespitosum	2.6	1.2	2.5
Vaccinium oxycoccus	12.1	10.3	3.1
Vaccinium uliginosum	0.8	0.5	0.9