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RESEARCH ARTICLE

Ecohydrological gradients and their restoration on the periphery of extracted peatlands

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The moss layer transfer technique is effective at restoring extracted peatland surfaces. However, remnant peatlands persist on the periphery of extracted surfaces. These remnant peatlands drop steeply to extracted surfaces, producing artificial ecotones that are more challenging to restore. We asked to what degree natural ecotones at undisturbed reference fens can act as models for the restoration of artificial ecotones around an extracted peatland, and whether management actions can ameliorate conditions in artificial ecotones. We compared changes in elevation, water table, peat, and multiple vegetation characteristics between natural ecotones and unmanaged artificial ecotones. We then clear-cut peripheral strips, completely filled perimeter canals, and smoothed peripheral slopes around sections of the extracted surfaces to assess whether hydrological conditions improved. Without management, artificial ecotones are not good models of natural ecotones. The elevation gradient is steep, and water tables drop steeply within 8 m of blocked perimeter canals, with possible effects at 25 m. The consequent vegetation had denser tree saplings, faster tree growth, almost no moss cover, and low moss species richness. After these management actions, water tables increased to within approximately 5 cm of those along natural ecotones. Future study is required to assess the extent of vegetation recovery, but these results hold promise for a more holistic rehabilitation of ecotones on the periphery of extracted peatland surfaces. We present recommendations to optimize the management actions on the periphery of extracted peatlands.

Key words: fens, hydrological management, peat harvesting, remnant organic soils, wetland ecotones

Implications for Practice

- Artificial ecotones with aberrant ecohydrological gradients persist between extracted peatland surfaces and peatland remnants on their periphery, even after restoration techniques have been applied to the extracted surfaces.
- Blocking contour canals at intervals is insufficient to return hydrological conditions along artificial ecotones to those similar to natural ecotones.
- Management actions on the periphery of extracted surfaces, including clear-cutting the edges of remnant peatlands, complete infilling of drainage canals, and surface reprofiling, improve hydrological conditions for peatland species establishment.

Introduction

Disturbed peatlands, following the extraction of peat, have very slow rates of natural revegetation (Lavoie et al. 2005). Active restoration is usually required. The Peatland Ecology Research Group (PERG) has developed techniques to restore the hydrologic regime and typical peatland plant communities of extracted peatlands (Quinty & Rochefort 2003; Graf & Rochefort 2016), which have proven to be effective in eastern Canada (González et al. 2014). However, these techniques generally only apply to extracted peatlands with unvegetated, almost level surfaces. Abrupt changes in topography, water table, and vegetation often persist between extracted peat surfaces and peatland remnants on their periphery, even after restoration techniques have been applied. These ecotones, which we term artificial ecotones, are often neglected during the peatland restoration process.

Horticultural peat companies preferably extract peat from open expanses or sparsely wooded areas of peatlands (Poulin et al. 1999), where the quality and the depth of the peat are optimal, but densely wooded peatlands are also used. They install drainage canals along the periphery of the extraction area to lower the water table, enabling the peat to dry and support the heavy machinery required for peat extraction. Peat is then extracted slowly over several decades. After peat extraction, a drop in surface elevation of up to several meters exists between the remnant peatlands and the extracted peat surfaces (Mioduszewski et al. 2013; Fig. 1). Sometimes, through the digging of peripheral drainage canals, peat berms are also created adjacent to extracted peat surfaces, which further accentuate the elevation drop (Jutras et al. 2007). Drainage canals can lower the

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Figure 1. An artificial ecotone on the periphery of the extracted section of the Bic-Saint-Fabien fen, showing the steep drop in elevation and change in vegetation.

water table in peatlands over variable distances from 5 to >30 m depending on the hydraulic conductivity of the peat (Boelter 1972; Berry & Jeglum 1991; Belleau et al. 1992; Prévost et al. 1997; Landry & Rochefort 2012). Even once drainage canals are blocked during restoration, which raises the water table to just below extracted peat surfaces, drainage effects can persist in the remnant peatlands on the periphery of the extracted surfaces. Lowering the peatland water table by 5 to 25 cm can increase the soil temperature and stimulate decomposition (Prévost et al. 1997) and also encourage the growth of vascular plants, especially pioneer herbs, ericaceous shrubs and trees, as well as forest bryophytes, while reducing the cover of *Sphagnum* and other typical peatland mosses (Poulin et al. 1999). The increase in taller woody plants also produces a positive feedback on the water table by increasing losses from interception of precipitation and evapotranspiration, which further lowers the water table (Van Seters & Price 2001; Fay & Lavoie 2009). If peat extraction takes place over several decades, the positive feedback of woody plants on the water table is accentuated. Steep drops in surface elevation on the periphery of extracted peatlands consequently become particularly hard to restore (Anderson et al. 1997).

Natural ecohydrological gradients of topography, water table, substrates, and vegetation often exist in undisturbed peatlands, between open peatland and peripheral forested peatlands (Gauthier & Grandtner 1975; Damman & Dowhan 1981; Bubier 1991; Poulin et al. 1999). Open peatlands are often slightly raised around perimeter forests and have shallow, stable water tables. They have thick deposits of poorly decomposed peat and low nutrient and mineral influences, and consequently the vegetation is dominated by *Sphagnum* and other peatland bryophytes. In contrast, peripheral forested peatlands slope very gently away from the open peatland. Their water tables are deeper and more fluctuating and they have more humified peats and more mineral influences. Their vegetation becomes dominated by closed canopy forests, with a ground cover of forest bryophytes (Paradis et al. 2015). Can managers use these ecohydrological gradients in natural peatlands as models to restore artificial ecotones on the periphery of extracted peatlands?

Current research suggests three possible strategies to restore artificial ecotones on the periphery of extracted peatlands. (1) Managers can completely fill the peripheral drainage canals using peat from the adjacent remnant peatlands (Mioduszewski et al. 2013; Scottish Natural Heritage 2015), especially where a strong slope exists between remnant and extracted peatlands (Verry 1988). (2) Managers can reprofile the topography of peripheral remnant peatlands to make them more amenable to restoration (Moreno-Mateos et al. 2012), by cutting the steep slopes along the edges of remnant peatlands and using this peat to backfill the edges of extracted surfaces and create a uniform gradual slope. (3) Managers can clear-cut trees along the edges of remnant peatlands in an attempt to reduce evapotranspiration and thereby increase the water table. Clear-cutting does increase the water table in cedar-dominated peatlands (Boulfroy et al. 2012) and clearing peripheral trees may also prevent tree colonization and consequent drying effects in extracted peat surfaces under restoration (Pellerin & Lavoie 2003; Fay & Lavoie 2009; Landry & Rochefort 2012).

In this study, we asked to what degree can unmanaged artificial ecotones on the periphery of extracted fens differ from the ecohydrological gradients found along natural ecotones at reference fens. We then test whether management actions along artificial ecotones aiming to (1) lower tree density, (2) completely fill peripheral drainage canals, and (3) reprofile peripheral topography can improve moisture conditions and better emulate natural ecotones. Finally, we propose best management actions to restore artificial ecotones on the periphery of extracted peatlands.

Methods

Study Areas

We conducted the research in southeastern Quebec, Canada, at extracted and undisturbed sections of the Bic-Saint-Fabien fen (48.322°N, 68.836°W; Fig. 2A), and at an undisturbed fen 14 km away, the Lac-des-iris fen (48.222°N, 68.960°W; Fig. 2B). Both sites are within the north temperate mixed forest region, specifically in the eastern forest zone of balsam fir-yellow birch (Saucier et al. 2011). The closest climate station at Rimouski (28 km ENE) has an average annual temperature of 4.4°C, with January and July means of −11.4 and 18.3°C, respectively, and with annual rainfall of 687 mm and annual snowfall of 274 cm (Government of Canada 2017). The growing season lasts between 175 and 182 days (Agrométéo Québec 2012).

About 13 ha in the central area of the original 41 ha Bic-Saint-Fabien fen was extracted for peat between 1953 and 2003. The extracted section of the fen was restored in winter 2009 by blocking the peripheral drainage canals at intervals with dams, which allowed them to remain active, but prevented permanent flooding of the center of the extracted peat surfaces (Leblanc et al. 2012). From the 13 rewetted ha, 2.8 ha

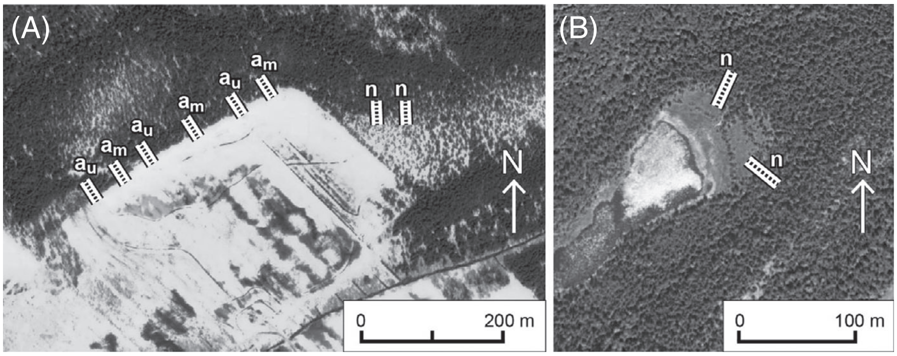

Figure 2. Study sites at (A) Bic-Saint-Fabien fen and (B) Lac-des-iris fen, showing transects along natural ecotones (n), and artificial ecotones, which were either left unmanaged (a_u) or were managed (a_m) during the winter of 2014–2015 (Aerial imagery: Google, DigitalGlobe, CNES/Airbus).

were revegetated by the moss layer transfer technique using fen plant material from a nearby drained lake surrounded by a cedar swamp. The rest of the rewetted fen was left to spontaneously revegetate.

Reference sites were located in an undisturbed section of the Bic-Saint-Fabien fen and at the Lac-des-iris fen. The undisturbed sections of the Bic-Saint-Fabien fen east of the extracted surface still support vegetation typical of open, moderately rich fens; they are dominated by *Thuja occidentalis* (Gauthier & Grandtner 1975) with interstitial pH of 6.5 ± 0.8 and electrical conductivity of 237 ± 136 μS/cm (mean ± SD, $n = 41$; L. Rochefort, unpublished data). The Lac-des-iris fen is also an undisturbed moderately rich fen with similar vegetation, dominated by *T. occidentalis*, with natural ecotones between open and forested fen vegetation (Bérubé et al. 2017) and with interstitial pH of 6.6 and electrical conductivity of 102 μS/cm. Our examination of historical aerial photography dating back to 1927 revealed that both reference sites have had similar vegetation since the 1930s

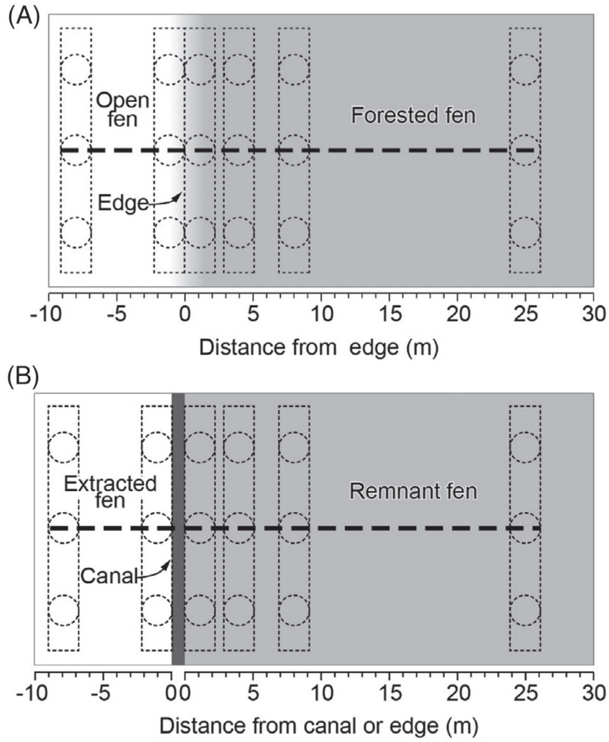

Figure 3. Transect sampling design along (A) natural ecotones and (B) artificial ecotones.

Ecotone Sampling and Analyses

We set up transects (1) along natural ecotones on the periphery of reference sites, and (2) along unmanaged artificial ecotones on the periphery of extracted peat surfaces (Fig. 2). Each transect ran parallel to the vegetation gradients, from 25 m within forested or remnant fen to 8 m within open or extracted fen (Fig. 3). We avoided areas with human disturbance within 50 m (clear cuts, secondary canals, agricultural fields, or roads), as determined by aerial photos and field visits. For natural ecotones, we placed two transects at each reference site along the open fen to forested fen gradient, as determined by aerial photography. For artificial ecotones, we placed six transects randomly along the northern periphery of the extracted peat surfaces. The remnant peatland was separated from the extracted peat surface by a 1 m large contour canal, blocked at its western end. We observed no water level gradient along the length of this canal. The effects of drainage canals on lateral water table lowering rarely exceed 10 m in cedar fens (Chimner & Hart 1996) or forested peatlands (Jutras et al. 2007). As such, we spaced transects at least 60 m apart to minimize any risk of hydrological influences between transects.

We sampled each transect in 2014 from within the forested or remnant fen to the open or extracted fen, at 25, 8, 4, 1.1, −1.1, −8 m from the forest edge along natural ecotones (Fig. 3A) or from the drainage canal along artificial ecotones (Fig. 3B). At each distance, we first set up 18 m wide by 2.2 m long strip plots (40 m^2) perpendicular to the transect. We measured the surface elevation relative to the level of water in the blocked drainage canal or the forest edge using a ZIPLEVEL precision pressurized hydrostatic altimeter (±1 mm precision; Technidea Corp., Escondido, CA, U.S.A.). We measured the depth to the water table along each transect in natural and unmanaged artificial ecotones between July 3 and 30, 2014, using an Odyssey multiprofile soil moisture recording system (±2.5 cm precision), which has a probe with four soil moisture sensors spaced 20 cm apart vertically. Since these sensors are showing contrasted values for saturated and unsaturated organic soils, the depth to the water table level was determined from the progressive insertion of the probe in peat at 5 cm intervals and the readings provided by each sensors. We had previously calibrated this procedure against the water table depth measured manually in perforated polyvinyl chloride pipe wells installed along a transect at Bic-Saint-Fabien.

We determined the peat depth at the center of each strip plot using fiberglass rods and sampled peat at 20 and 60 cm depths with a soil auger to assess the degree of decomposition on the von Post scale (Clymo 1983; Soil Classification Working Group 1998). We counted all stems of woody plants greater than 1.3 m tall in each strip plot and measured their basal area using calipers. We also cored the two largest trees in each plot at a height of 1.3 m using an increment corer, mostly *T. occidentalis* (102 trees) with a few *Larix laricina* and *Picea mariana* (seven trees). Later in the laboratory, we sanded the increment cores and used WinDendro software (Regent Instruments Inc., Sainte-Foy, Quebec, Canada) to determine their age, as well as their average annual diameter increment since 1953, when the Bic-Saint-Fabien fen was first extracted. For each strip plot, we averaged the tree ages and average diameter increment since 1953. Within each strip plot, we also installed three evenly spaced circular subplots (2.2 m diameter; 4 m^2). In each, we measured canopy cover at 1.3 m height in cardinal directions using a convex densiometer (±3.1% precision), and we visually assessed the cover and species composition of herbs and low shrubs less than 1.3 m tall. Finally, we randomly placed a 0.06-m^2 mini-plot within each 4-m^2 subplot and estimated the cover and species composition of bryophytes. We averaged canopy cover and low shrub, herb, and bryophyte cover across the set of three subplots at each distance.

We analyzed the changes in elevation, water table depth, peat depth, degree of decomposition, canopy cover, basal area, stem density (<8 and >8 cm), tree age, average tree diameter increment since peat extraction, species richness, and total cover in vegetation strata using a hierarchical design at the six distances (25, 8, 4, 1.1, −1.1, and −8 m) along natural versus unmanaged artificial ecotones. We considered the distances along each transect as a repeatedly measured categorical variable, nested within the ecotone type fixed categorical variable. We focused on the fixed effect of ecotone type and the interaction of ecotone type with distance, and did not include the distance effect in the final model. We analyzed for significant interaction effects across all ecotone by distances plots using Tukey's a posteriori tests with a type I error rate of 0.05. We examined residual plots to verify assumptions of the analyses and log-transformed the data where necessary. We conducted these analyses with mixed models and maximum likelihood inference using the nlme and multcomp packages of R (R Development Core Team 2011).

We also used multivariate regression trees to test for differences in vegetation structure and composition among the ecotone types as a function of environmental variables. We first tested for collinearity between environmental variables using Pearson correlation analyses, and we retained elevation, water table, peat decomposition at 20 cm, canopy cover, and stem density for use in the regression tree analyses. We transformed species abundance data using Hellinger transformation to avoid overweighting rare species (Legendre & Gallagher 2001). We then used the vegan and mvpart packages in R to determine the regression trees. We set the point at which species were discriminant at 9% to allow for at least one species per regression node.

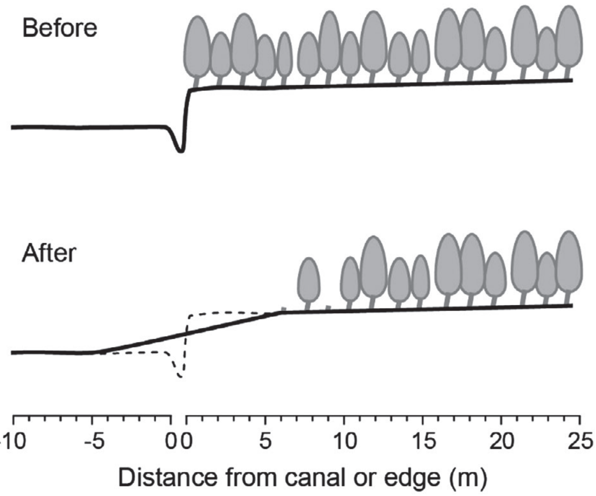

Figure 4. Cross section of an artificial ecotone on the periphery of an extracted surface before (top) and after 20 m wide management treatments of tree cutting, canal filling and cutting, and filling of the peat surface.

Management Treatments and Water Level Changes

Between December 2014 and February 2015, we applied three management operations to each of three alternate transects along artificial ecotones at Bic-Saint-Fabien (Fig. 2). We applied these management operations to sections roughly 20 m wide on the periphery of extracted surfaces (Fig. 4). The first step we made on each of the three transects was to clear-cut trees in the remnant peatland within 5 m of the drainage canal and to cut selectively large diameter trees within 5–8 m of the canal to reduce potential evapotranspiration and interception. Second, an excavator completely filled the drainage canal on all three transects using peat from the berms and the remnant peatland. Third, the excavator reprofiled the peripheral topography of all three transects by cutting peat within 5 m of the adjacent peatland and used the peat to backfill the edges of the extracted peatland, producing a gradual peat slope extending over approximately 10 m from the remnant peatland to the extracted surface.

We measured the surface elevation at 21 points along the managed artificial ecotones in 2015, relative to the water level in the drainage canal in 2014. We also measured the water table on May 26–28 and on July 6–7, 2015, at 21 points along each transect in natural and unmanaged and managed artificial ecotones using an Odyssey multiprofile soil moisture recording system (Dataflow Systems Limited, Christchurch, New Zealand), as above.

Results

Natural Versus Unmanaged Artificial Ecotones

The surface elevation of the plots did not change along the natural ecotone, but the surface elevation along the unmanaged artificial ecotones dropped 1.45 m on average from the 25 m distance in the remnant peatland to the −8 m distance on the extracted peat surface (Fig. 5A). This represented a mean slope of 6% over the 33 m long transects and 23% between the 1 and −1 m distances. The depth to the water table did not change along the natural ecotones (mean: −8.9 cm), and it was lower in the unmanaged artificial ecotones (mean: −22.0 cm; $p = 0.0048$; Fig. 5B), but there was a strong interaction; the water table dropped to a mean minimum of 39 cm below the surface at the 4 m distance from the peripheral drainage canal.

We found no significant differences in peat thickness along natural and artificial ecotones ($p = 0.13$), but an interaction was evident, with the extracted peat surfaces along the unmanaged artificial ecotones having shallower peats, as expected because of peat extraction (Fig. 5C). The von Post degree of decomposition of the peat at both 20 and 60 cm depths did not differ between the ecotones ($p > 0.43$), but once more an interaction was present; the open sections of the natural ecotone had less decomposed peat (20 cm depth at −8 m: 4.0 ± 0.3), and the forested sections had more decomposed peat (20 cm depth at 25 m: von Post 5.5 ± 0.3), but there was no change along the unmanaged artificial ecotone (Fig. 5D).

The canopy cover changed along the transects, of course, since we chose the positions of the transects based on this parameter, but the transition in cover was gradual along the natural ecotones (4 m: 83%; −8 m: 39%) and much more abrupt along the unmanaged artificial ecotones (4 m: 94%; −8 m: 4%; Fig. 5E). A similar trend was also visible in terms of the basal area of woody stems at 1.3 m height (Fig. 5F). Again, there was no difference in average basal area between the ecotone types ($p = 0.36$), but there was a gradual change along natural ecotones (4 m: 36 m^2/ha; −8 m: 12 m^2/ha) and a more abrupt change along the unmanaged artificial ecotones (4 m: 59 m^2/ha; −8 m: 0.2 m^2/ha). The density of woody stems greater than 8 cm in diameter closely follows the change in canopy cover and basal area, with no change between the ecotones ($p = 0.40$), but with a gradual change along natural transect (4 m: 1720/ha; −8 m: 370/ha) and again an abrupt change along the unmanaged artificial ecotones (4 m: 2090/ha; −8 m: 0/ha; Fig. 5G). In contrast, while the overall density of woody plants less than 8 cm in diameter does not differ between the ecotone types ($p = 0.93$), an interaction appears to be present (Fig. 5H); little pattern occurs along the natural ecotones (mean: 6,350/ha), but, within the remnant peatland sections of the unmanaged artificial ecotones, more than twice the number of smaller diameter woody plants are present at 1–8 m (mean: 14,500/ha) as compared to the 25 m distance (mean: 5,780/ha). When we examined the mean age of trees, those along the natural ecotones are of a similar age (mean: 82.4 years), while those along the unmanaged artificial ecotones are younger closer to the drainage canal (1–4 m: 51.2 years; 25 m: 86 years; Fig. 5I). Similarly, the mean diameter increment of trees does not change along the natural ecotones (mean: 0.8 mm/year), but along the unmanaged artificial ecotones, the diameter increment is greater for trees closer to the drainage canal (1–4 m: 1.4 mm/year; 25 m: 0.9 mm/year; Fig. 5J). Note that the mean age and diameter increment of trees in natural ecotones resembles those found at 25 m from the drainage canal in the unmanaged artificial ecotones.

We observed little change in the richness of trees per plot ($p = 0.42$) between ecotones, nor in the cover or species richness of shrubs (cover: $p = 0.88$; richness: $p = 0.15$; not illustrated). However, there was higher herbaceous cover along the natural ecotones (mean: 37%) than along the unmanaged artificial ecotones (mean: 15%: $p = 0.0021$; Fig. 5K). Herbaceous species richness was also higher in natural ecotones (mean: 14.5) than along unmanaged artificial ecotones (mean: 9.8; $p = 0.02$; Fig. 5L). Similarly, there was higher bryophyte cover along the natural ecotones (mean: 48.7%) than the unmanaged artificial ecotones (mean: 7%; $p = 0.0012$; Fig. 5M). Likewise, there was higher bryophyte species richness per plot along the natural ecotones (mean: 2.3) than along the unmanaged artificial ecotones (mean: 0.6; $p = 0.0001$; Fig. 5N). Cover and species richness of herbaceous plants and bryophytes are most similar between these ecotone types at the 25 m distance from the edge or drainage canal.

The multivariate regression tree produced a dendrogram with four branches and five groups explaining a total of 31% of the variation (Fig. 6). Canopy cover explained 11% of the variation in species composition along natural and unmanaged artificial ecotones. Plots with greater than 83% average canopy cover were associated with more small diameter *Thuja occidentalis*, and this was especially the case along artificial ecotones near the drainage canal (1, 4, and 8 m). In contrast, closed canopy sites along natural ecotones (4, 8, and 25 m) resembled the natural ecotone plots furthest from the canal (25 m) and were characterized by the presence of *Sphagnum warnstorfii*. Plots with ≤83% canopy cover were separated in natural ecotones and artificial ecotones, with the natural ecotones having *S. warnstorfii*. The open artificial ecotones were further separated into two groups based on the von Post degree of decomposition at 20 cm, with either less decomposed peat, or mostly more decomposed peats, where *Rubus idaeus* was more prevalent.

Effects of Management Treatments

After the management treatments were applied to the artificial ecotones, the elevation still dropped by between 165 and 39 cm between the 8 and −8 m relative to the filled drainage canal, for an average slope of 7%, but the change was much more gradual, with few abrupt changes (Fig. 7). The consequent water table in the managed artificial ecotones was intermediate in 2015 between the natural ecotones and unmanaged artificial ecotones (Fig. 8). Specifically, the water table in the remnant peatlands between 25 and 8 m from the prior edge averaged 11 and 15 cm below the surface in May and July, respectively. This was just slightly lower than found across the natural ecotones (7.5–12 cm depth, May and July), but higher than found in the unmanaged artificial ecotones between 25 and 8 m (17–21 cm depth, May and July). The water table depth

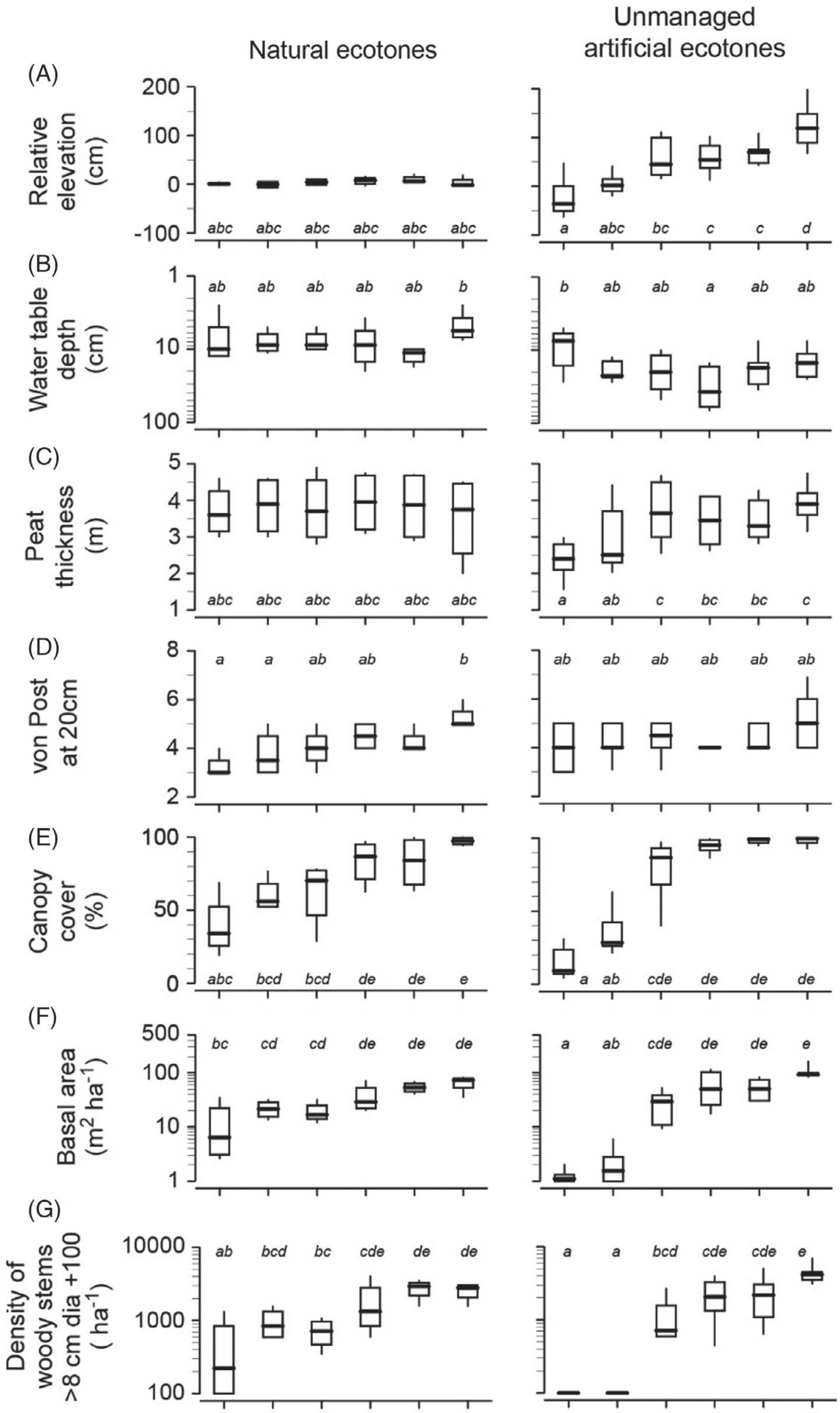

Figure 5. Box plots along the natural ecotones (left) and unmanaged artificial ecotones (right) for (A) elevation, (B) water table depth in July 2014, (C) peat thickness, (D) von Post decomposition at 20 cm depth, (E) canopy cover, (F) basal area, (G) density of woody stems greater than 8 cm in diameter, (H) density of woody stems less than 8 cm in diameter, (I) average age of trees, (J) average diameter increment of trees since 1953 when peat extraction began, (K) herbaceous cover, (L) herbaceous species richness, (M) bryophyte cover, and (N) bryophyte species richness. Small script letters above the box plots represent homogeneous groups across both natural and unmanaged artificial ecotones, based on Tukey tests with a 5% type I error rate.

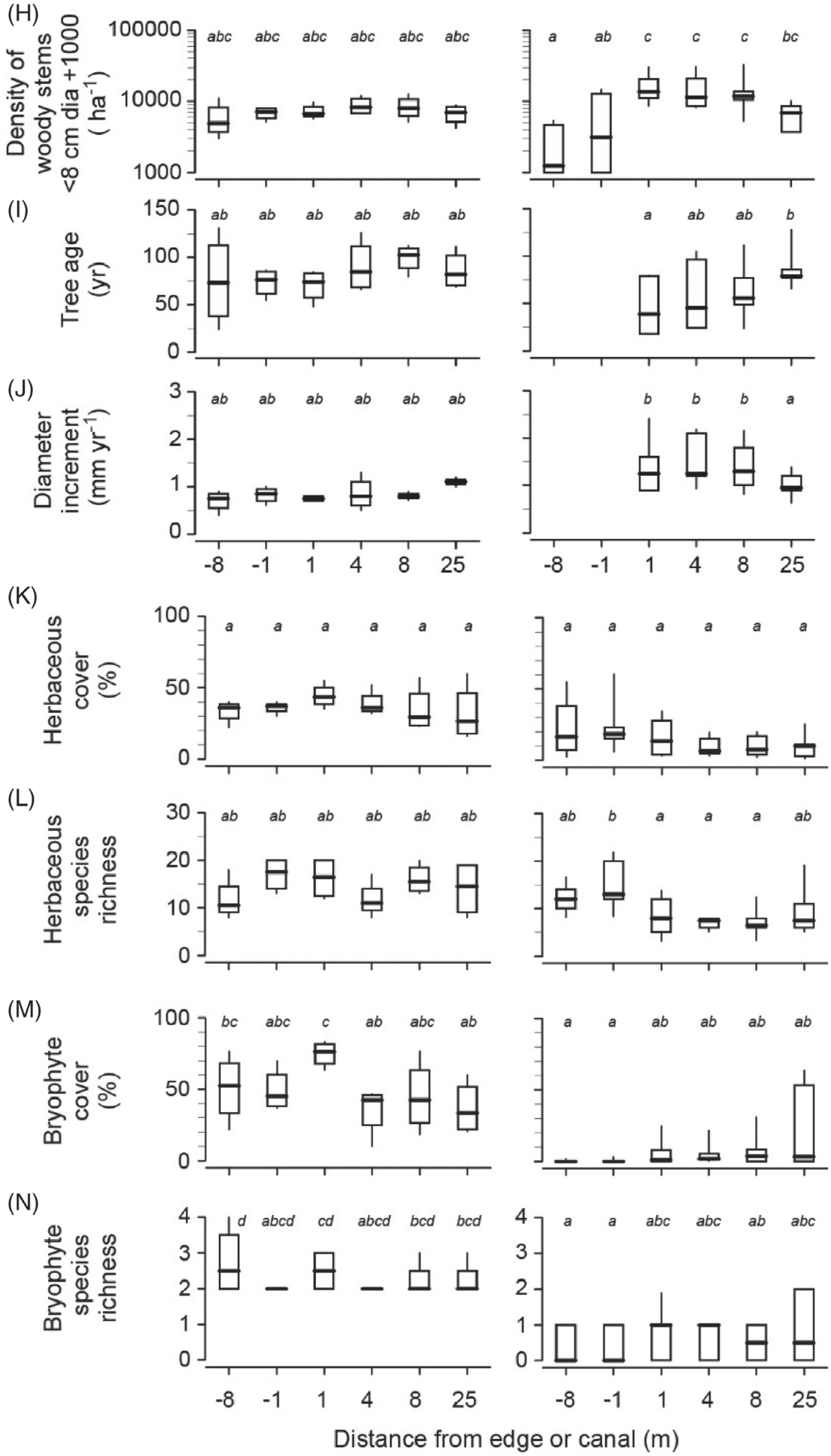

Figure 5. Continued.

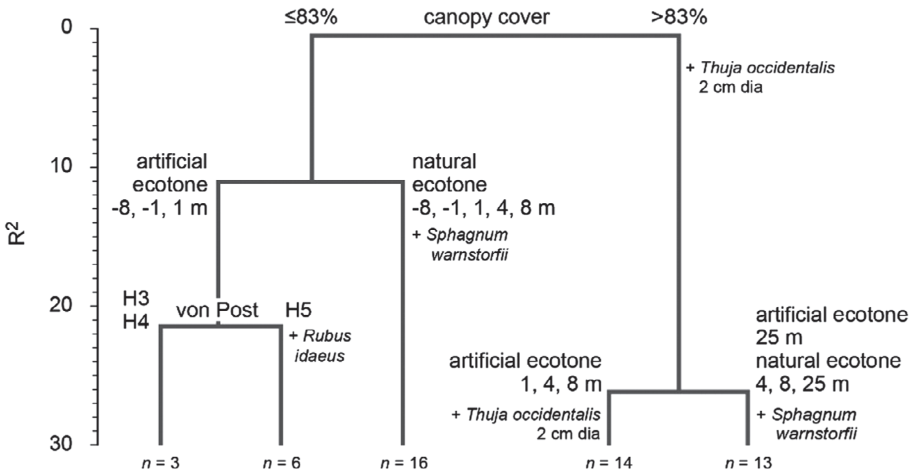

Figure 6. Dendrogram of the multivariate regression tree.

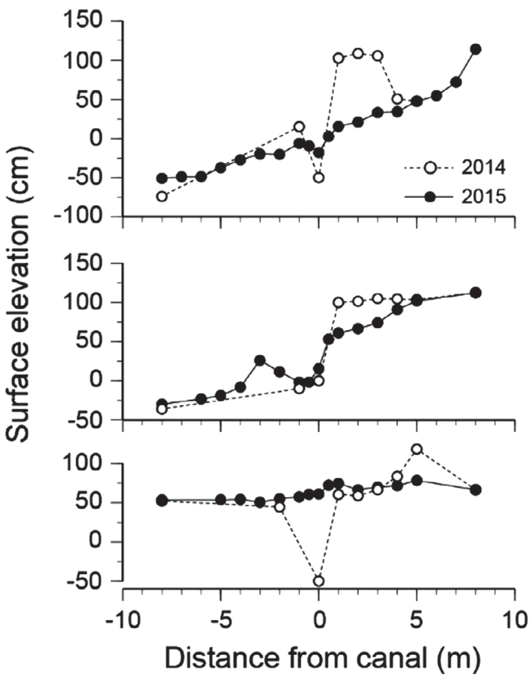

Figure 7. The relative surface elevations along the three artificial ecotone transects in 2014 and in 2015 after cutting and backfilling.

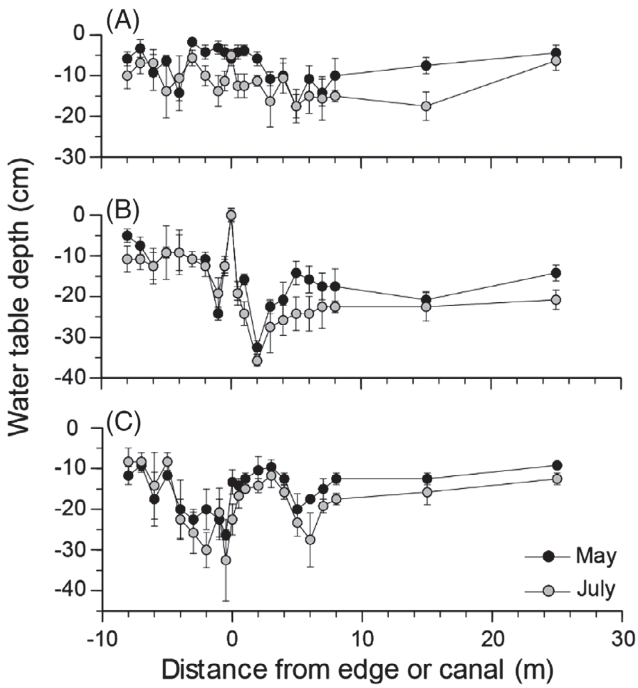

Figure 8. Changes in water table depth on May 26–28 and on July 6–7, 2015, along (A) natural ecotones, (B) unmanaged artificial ecotones, and (C) managed artificial ecotones. The error bars represent standard error.

in the section of the managed artificial peatlands that was cut and backfilled (5 to −5 m) was more variable, because of some remaining nonuniformity in the grade, but the water table remained intermediate between the natural and unmanaged artificial ecotones.

Discussion

Without management, the artificial ecotones on the periphery of extracted surfaces did not strongly emulate natural ecotones. Differences existed in topography and water table, in peat thickness and humification, and in the vegetation: tree, herb, and bryophyte strata. Unmanaged artificial ecotones had moderate to steep slopes, especially near the canal, and, even though the drainage canal was previously dammed at intervals to raise the water table on the extracted surfaces, the canals continued to drain the remnant peatlands. The water table along artificial ecotones consequently dropped within the first 5 m of the canal. These water level declines were even noticeable at 25 m from the edge along artificial ecotones, in both years, being 10 cm lower in July 2014 and 10 and 15 cm lower in May and July 2015, respectively. Other researchers have shown zones of influence of drainage canals in peatlands to be from 5 m in moderately decomposed peats (Boelter 1972; Chimner & Hart 1996), extending to within 15 or 30 m in poorly decomposed peats with greater hydraulic conductivity (Belleau et al. 1992; Prévost et al. 1997). Such water table declines are sufficient to modify soil processes (Prévost et al. 1997), change the growth and recruitment of *Thuja occidentalis* in fens (LeBarron & Neetzel 1942; Chimner & Hart 1996), and shift species composition away from typical peatland species assemblages (Poulin et al. 1999; Korpela 2004).

We did not find any change in peat humification closer to the drainage canals in artificial ecotones as a result of peatland drainage since 1953, as found in other studies (Prévost et al. 1997). Given that peat humification did change along natural ecotones, with less decomposed peat closer to the open peatland, it is possible that a similar gradient in peat humification existed along artificial ecotones prior to drainage, which is obscured by peat decomposition effects over the last half century.

The vegetation was certainly impacted by the drainage within at least 8 m from the blocked canals. Tree growth increased since the canals were dug and peatland extraction began, as did the recruitment and density of less than 8 cm diameter tree saplings. These effects on trees must also increase the interception of precipitation and evapotranspiration (Van Seters & Price 2001; Fay & Lavoie 2009), which further lowers the water table. The drainage effects within 8 m of the canal also appear to be responsible for the near disappearance of bryophytes, especially *Sphagnum*, as found in other studies (Laine et al. 1995; Campbell et al. 2003). The drainage of peatlands reduces surface moisture conditions (Price 1997), which may directly reduce *Sphagnum* growth and presence (Hayward & Clymo 1982; Price & Whitehead 2001), but the increased shade and litter fall from taller vegetation may also indirectly contribute to the loss of *Sphagnum* (Larmola et al. 2013).

At 25 m within the unmanaged artificial ecotones, the growth of trees and vegetation most resembled the vegetation in the forested sections of the natural ecotones, and *Sphagnum warnstorfii* was present as an indicator of reference conditions. But even here, the cover and richness of bryophytes was lower than in natural ecotones, which may suggest the continued effects of drainage or an unspecified edge effect on the periphery of extracted surfaces. Without intervention, it is apparent that the transformation of the remnant peatlands along unmanaged artificial ecotones could continue toward drier forested ecosystems.

The management actions we applied had a positive impact on the water table along artificial ecotones. The water table at 25 m from the prior canal was now just 5–6 cm lower in May and July 2015, respectively, than at the same distances in the natural ecotones and 10 cm higher than at 25 m along unmanaged artificial ecotones. The effect was more variable within the reprofiling zone from 5 to −5 m from the prior canal, likely because of the variability in producing a consistent grade of slope, but the water table in this section was still generally higher than along unmanaged artificial ecotones. Open habitats with water tables within 10 cm of the surface are more conducive for *Sphagnum* survival (Price et al. 2016), higher photosynthetic capacity (Rydin & McDonald 1985), and growth (Grosvernier et al. 1997). Minerotrophic hummock mosses such as *S. warnstorfii* should thrive under these conditions. Natural colonization of peatland bryophytes and vegetation may occur or accepted restoration practices of spreading *Sphagnum* fragments and straw mulches could be applied. However, the success of natural recolonization or restoration would need to be further studied to verify for shifts toward vegetation resembling natural ecotones.

Natural ecotones usually show a gentle slope away from the central open sections of a peatland with poorly decomposed peat toward the surrounding forest with more decomposed peats having a lower hydraulic conductivity (Damman & Dowhan 1981; Bubier 1991; Baird et al. 2008; Langlois et al. 2015; Paradis et al. 2015). Although we observed no slope along the natural ecotones we studied, the slopes along our managed artificial ecotones ran in the opposite direction, from the surrounding forest toward the open extracted peat surfaces. Peat also remained mesic along these artificial gradients, so hydraulic conductivity should be generally constant along artificial ecotones. The hydrology of these managed artificial ecotones would consequently differ from natural ecotones. The hydrological conditions of managed artificial ecotones, and the consequent vegetation, will depend on the size and hydrology of the peatland fragments up gradient, instead of depending on the hydrology of central peatlands. Given this difference between natural and artificial ecotones, further study is also warranted on the longer-term hydrological behavior of managed artificial ecotones.

In general, our management actions show some promise for restoring the underlying conditions of artificial ecotones toward those in more natural ecotones. We acknowledge that we cannot clearly separate the effects of clearcutting from that of drainage canal infilling or surface reprofiling. Further study is required. However, based on the results of this and other studies, we can offer several interim recommendations of management actions, which should help maintain and restore more natural ecotones on the periphery of extracted peatlands. (1) Companies should not extract peat to the limit of their properties and retain an unextracted strip, in order to have sufficient space to apply management operations on the periphery of extracted surfaces. In other jurisdictions, such as Alberta, peat producers have adopted this as best management practices. (2) Trees should be clear-cut within at least 8 m of peripheral drainage canals, since, as we have shown, this is the zone in which the largest impacts on the water table occur. (3) This clear-cutting could begin at the start of peat extraction operations to limit the effects of the interception of precipitation and evapotranspiration by trees, and companies could also periodically clear-cut this strip to maintain open peatland vegetation. After extraction ceases, remaining trees within the management strip should be cut before canal filling or reprofiling occurs. (4) Peripheral drainage canals should be completely filled and not just blocked at intervals. Simply blocking the peripheral drainage canal at intervals, as was done in this study along the unmanaged artificial ecotones, was insufficient to prevent drainage and its effects on tree growth and density. (5) Reprofiling of the peripheral peatlands should aim for a slope of 7% or less over 8 m on either side of the filled drainage canal. This was the maximum slope we obtained in our study, and it was successful in raising the water table. However, this is an interim guideline, to be corroborated at other sites. (6) Reprofiling should aim for a uniformly gentle slope, without abrupt changes, especially at the upper and lower limits of the 8 m management strip. Woody debris should also be removed from fill material to ensure the constant grading toward a gentle slope. (7) Reprofiling should take place when there is little or no snow cover, because our management experiment showed that deep snow and frozen soils make it difficult to achieve a uniformly gentle slope. (8) Where changes in elevation are, or planned to be, particularly large, the peripheral management strip may have to be significantly wider. We cannot provide specific guidance as to suitable distances because this would require testing at other sites with more extreme elevation drops, beyond the scope of this study. (9) The moss layer transfer technique (Graf et al. 2012) could be applied to peripheral zones after clear-cutting and reprofiling are complete. As said previously, the water table rise may facilitate the establishment of *Sphagnum* species, which are a key species in peatlands restoration (Rochefort 2000). (10) The vegetation should be monitored after management actions to ensure that desirable peatland species establish. Monitoring intervals of 2–5 years after peatland restoration actions have been suggested (Quinty & Rochefort 2003).

In conclusion, this study allowed us to quantify the differences in topography, water table, peat, and vegetation characteristics between natural ecotones and unmanaged artificial ecotones on the periphery of extracted peatlands. We were also able to confirm that a combination of management actions, including the clear-cutting of trees, the complete filling of drainage canals, and surface reprofiling of peripheral remnant peatlands, can help to raise water tables. Further study is required to assess to what extent vegetation and ecosystem processes return in managed artificial ecotones and how they will integrate into more holistic peatland ecosystem restoration practices.

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