

Do power line rights-of-way facilitate the spread of non-peatland and invasive plants in bogs and fens?

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Abstract: Linear infrastructures are known to facilitate the spread of undesirable species in ecosystems. Compared with other types of infrastructure, the role of power line rights-of-way (ROWs) as dispersal vectors remains poorly understood, especially with regard to peatlands. The aim of our study was to evaluate their impacts on the vegetation of ombrotrophic (bog) and minerotrophic (fen) peatlands. The vegetation communities within and adjacent to power line ROWs were sampled in 23 bogs and 11 fens in southern Québec. In fens, invasive species were found in abundance along the first 250 m within ROWs, while native non-peatland species were able to spread into entire ROWs. Invasive species were also able to colonize the adjacent fen habitats but were mostly concentrated in the first 4 m from ROW edges. Some species were, however, able to establish at more than 43 m from ROWs. Invasive and native non-peatland species were mostly restricted to the first 31 m within ROWs intersecting a bog and almost none dispersed in the adjacent bog habitats. Overall, the average cover of native non-peatland and invasive species in ROWs was mostly related to intrinsic abiotic conditions such as water pH, water conductivity, and water table level, while landscape surrounding the peatland and historical variables (e.g., time elapsed since the construction of the ROW) had few impacts in both bogs and fens.

Key words: corridors, invasive species, edge effect, disturbance, peatland.

Résumé : Les infrastructures linéaires peuvent faciliter la dispersion des espèces indésirables. Comparativement aux autres types d'infrastructures, le rôle des emprises de lignes électriques comme vecteurs de dispersion demeure peu connu, surtout dans les tourbières. L'objectif de notre étude était d'évaluer les impacts de ces emprises sur la végétation des tourbières ombrotrophes «bogs» et minérotrophes «fens». Nous avons échantillonné la végétation de 23 emprises de lignes électriques traversant des bogs et de 11 autres traversant des fens, dans le sud du Québec. Nous avons également échantillonné la flore des habitats tourbeux adjacents à ces emprises. Dans les emprises traversant les fens, les espèces envahissantes étaient présentes en abondance dans les 250 premiers mètres, alors que les espèces indigènes non-tourbières pouvaient se propager dans l'ensemble des emprises. Les espèces envahissantes étaient également présentes dans les habitats adjacents aux fens, mais surtout dans les quatre premiers mètres en bordure des emprises. Certaines de ces espèces étaient toutefois encore présentes à plus de 43 mètres des emprises. À l'inverse, les espèces envahissantes et non-tourbières étaient surtout confinées le long des 31 premiers mètres dans les emprises traversant les bogs et pratiquement aucune n'était présente dans les habitats adjacents aux bogs. Dans l'ensemble, la susceptibilité des tourbières à l'envahissement dans les emprises est surtout liée aux conditions abiotiques des sites comme le pH et la conductivité de l'eau, et le niveau de la nappe phréatique, tandis que le paysage qui entoure les tourbières et les variables historiques (p. ex., le temps écoulé depuis la construction de l'emprise) ont peu d'effets sur les bogs et les fens.

Mots-clés : corridors, espèces envahissantes, effet de bordure, perturbation, tourbière.

Introduction

Anthropogenic corridors, such as power lines, roads, and trails are common features in urban, suburban, and rural landscapes. Despite their undeniable importance for human activities, the creation and maintenance of these linear structures and their associated rights-of-way (ROWs) may have detrimental effects on the environment by acting as dispersal vectors for invasive plant species (Benninger-Truax et al.

1992; Jodoin et al. 2008; Kalwij et al. 2008). The establishment and spread of invasive plant species in such corridors are facilitated by several factors such as the increase in light intensity and temperature owing to the eradication of tall indigenous species (Parendes and Jones 2000; Delgado et al. 2007), the chemical and physical disturbance of the upper soil layers (Hobbs and Atkins 1988; Johnston and Johnston 2004; Jodoin et al. 2008), the reduction of competition (Parendes and Jones 2000), and the decrease of wind barriers to

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pollen and seed dispersal (Hill et al. 1995; Parendes and Jones 2000).

Anthropogenic corridors may also facilitate the spread of invasive plant species to adjacent ecosystems through the creation of new sharp boundaries (Fraver 1994; Harrison et al. 2002; Arevalo et al. 2008). The width of the adjacent ecosystems affected by the corridor (or the depth of edge influence) varies depending on the species involved (Euskirchen et al. 2001), the linear feature type (Parendes and Jones 2000), and the intersected community (Chen et al. 1992; Hansen and Clevenger 2005; Delgado et al. 2007). For instance, the depth of edge influence of highways and railways in western Canada is more than 150 m in grasslands but only 10 m in forests (Hansen and Clevenger 2005). Ecosystems with open canopies are indeed more prone to colonization by invasive species than treed ecosystems, since few invasive species, especially exotic ones, are adapted to low light availability (Parendes and Jones 2000).

Compared with other types of infrastructure, scientific understanding of the impact of power line ROWs is lacking, especially with regard to peatlands. Nearly all studies on the subject have aimed at understanding the impact of the construction of a power line ROW on peatland plant communities by comparing plots in the ROW with plots in undisturbed control areas within the same sites, regardless of gradients within and from the ROW (e.g., Grigal 1985; Nickerson and Thibodeau 1984; Thibodeau and Nickerson 1986; Nickerson et al. 1989). Discrepancies in results between the few existing studies make generalization difficult to set. For example, in a peatland of northern Minnesota, Grigal (1985) showed that major compositional changes occurred in low shrub ombrotrophic vegetation type following construction but that all vegetation strata returned to their previous status by the second growing season. In contrast, in a Massachusetts shrubby ombrotrophic peatland, Nickerson et al. (1989) found that the changes induced by ROW construction were still apparent 10 years later. Differences are likely due to the fact that construction activities in the Nickerson et al. (1989) study took place during summer when vehicle traffic usually causes severe disturbances to the upper soil layers instead of during winter, as in Grigal (1985) when the frozen ground reduces the impacts. The aim of the present study was to evaluate the impact of power line ROWs on the vegetation of ombrotrophic (bog) and minerotrophic (fen) peatlands in Québec. Our specific objectives were (i) to determine whether power line ROWs act as dispersal vectors for native non-peatland and invasive species, (ii) to estimate the depth of edge influence of these species at ROW–peatland edges, (iii) to evaluate the spatial extent of the effect of ROWs on native peatland species and nonvascular species, and (iv) to identify which environmental factors favour plant invasiveness in the studied peatlands. We hypothesized that power line ROWs are effective corridors of invasion for native non-peatland and invasive species in both bogs and fens, meaning that their covers would be similar from the margin toward the centre of the peatlands. We, however, expected that the spatial extent of their impacts on the vegetation of adjacent peatland habitats would be less significant in bogs than in fens given the limiting environmental conditions in bogs.

Material and methods

Study area and sites

The study area is located in the St. Lawrence Lowlands of southern Québec and extends from 45°N to 48°N latitude and 69°W to 75°W longitude (Fig. 1). The area is enclosed by the Canadian Shield to the north and the Appalachian Mountains to the south and east. The Lowlands have a flat topography and are characterized by deep arable soils derived from glacial and marine deposits. The rich soils support agricultural land use (cropland and pasture) on large areas, especially on the south shore of the St. Lawrence River. Urban land uses occupy about 10% of the area and are concentrated around the cities of Montréal and Québec (Fig. 1). Exotic species are widespread in the landscape of the studied region, composing between 5% and 43% of the vascular floras published in southern Québec (C. Lavoie, unpublished data). They may even reach up to 60% of the vascular flora in disturbed areas (Lavoie and Saint-Louis 2008). The mean annual temperature of the study area fluctuates from 3.2 °C in the northeast to 6.7 °C in the southwest (Environment Canada 2008). Average precipitation ranges from a maximum of 1056 mm in the eastern part of the region to a minimum of 963 mm in the west, of which 20% and 29% falls as snow, respectively (Environment Canada 2008).

Raised bogs dominated by ericaceous shrubs, *Sphagnum* mosses, and *Picea mariana* (Mill.) Britt. thickets are scattered over the study areas. Fens are much less abundant and are mostly wooded and shrubby. They are also characterized by a diverse herbaceous stratum and by the abundance of brown mosses. Based on the *Atlas des tourbières du Québec méridional* (Buteau 1989), air photo interpretation, and field surveys, at least 56 peatlands are intersected by at least one of several power line ROWs in the study area. Of these, we sampled 23 bogs and 11 fens (Fig. 1). Bogs and fens were distinguished botanically on the basis of the presence of brown mosses in fens and of *Sphagnum* mosses in bogs. Bogs mainly ranged in size from 3 to 925 ha (one bog was 4150 ha), while fens ranged from 10 to 990 ha. Mean pH was 3.92 ± 0.26 for the bogs and 5.80 ± 0.87 for the fens. Only peatlands easily accessible and with no recent evidence of human disturbance other than the power line ROW were sampled. All but two sampled bogs were open or semiforested (sparse cover of small woody vegetation); two were wooded (dense cover of tall woody vegetation). All sampled fens were wooded. In most of the selected peatlands power lines were established between 1949 and 1987, except in seven bogs where the construction only dates back to 1996. In this study, power line ROWs were defined as the sectors where recurrent maintenance treatments (selective manual tree cutting) were evident. When present, access roads and drainage ditches were considered to be part of the ROWs.

Vegetation sampling

Three transects were established in each peatland sampled. The first one was placed in the centre of the ROW going from the peatland margin to the peatland centre (Fig. 2). The two other transects, positioned 20 m apart (10 m on each side of the peatland centre), were located parallel to each other and perpendicular to the ROW, going

Fig. 1. Location of the 23 bogs and 11 fens sampled, southern Québec.

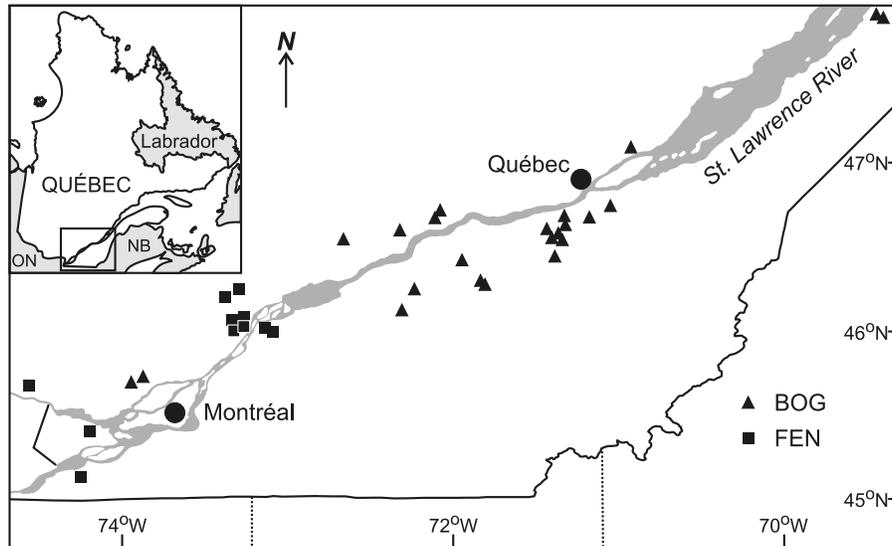
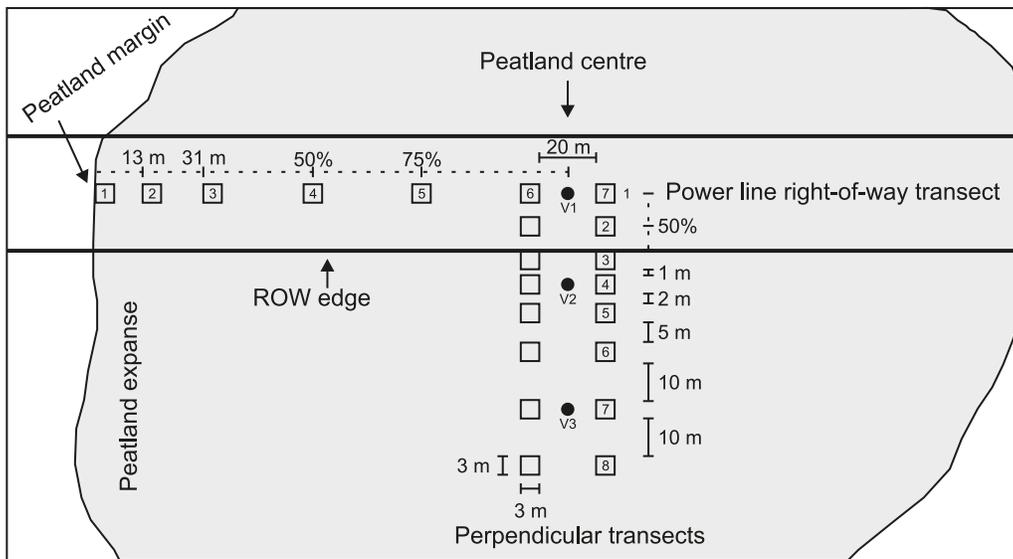


Fig. 2. Representative illustration of peatland sampling design. The number in each sampling plot refers to its position number on transects. V1, V2, and V3 indicate the three locations where the abiotic variables were sampled.



from the centre of the ROW into the peatland (Fig. 2). Perpendicular transects were located near the centre of the peatland to reduce the probability of detecting invaders coming from the surrounding matrix through the natural peatland margins. To avoid any confusion, the term margin will only refer to the peatland limits (peat thickness ≥ 30 cm) and the term edge will refer to the transition between the ROW and the natural peatland expanse. Each peatland was sampled once in 2006 or 2007. Voucher specimens were deposited in the Marie-Victorin Herbarium (MT, Montréal, Québec).

Power line ROW transect

In each peatland sampled, seven $3\text{ m} \times 3\text{ m}$ plots were established along the ROW transect (Fig. 2). The first three plots were placed at fixed distances, i.e. at the peatland margin (0 m from the margin) and at 10 and 15 m from the end of the previous plot (which corresponds to 13 and 31 m from the margin, respectively). The fourth and fifth plots

were set at, respectively, 50% and 75% of the distance between the margin and the centre of the peatland. Finally, the sixth and seventh plots were established at the centre of the peatland and spaced 20 m apart. We did not sample the fourth plot when the distance between the margin and the centre of the peatland was less than 65 m (one fen) and the fourth and fifth plots when the distance was less than 60 m (one fen, four bogs). In very small sites (distance between the margin and the centre of the peatland less than 45 m), only the first, second, sixth, and seventh plots were sampled (one bog and one fen). Within each $3\text{ m} \times 3\text{ m}$ plot, three 0.33 m^2 circular subplots were placed randomly to facilitate rapid accuracy assessments of covers, especially of mosses for which percent covers are more difficult to evaluate within large plots. In these subplots, the cover of all vascular and nonvascular species was visually estimated to the nearest 1% when cover was below 10% and to the nearest 5% when cover was between 10% and 100%.

Perpendicular transects

The two perpendicular transects began at the sixth and seventh plots of the power line ROW transect and were placed toward the peatland expanse (Fig. 2). The first plots of the two transects are thus the same as plots six and seven of the ROW transect. The second plot of each transect was placed halfway between the centre and the edge of the ROW. When the ROW was too narrow (less than 20 m wide) to allow two plots to be sampled, only the centre plot was sampled (three bogs). Six additional plots were set entirely in the adjacent peatland, one located at the edge and the others, respectively, spaced 1, 2, 5, 10, and 10 m from the end of the previous plot (which corresponds to 0, 4, 9, 17, 30, and 43 m from the edge; Fig. 2). The last two plots are located at a greater distance than previous studies used to set their control plots on presumably undisturbed communities (MacLellan and Stewart 1986). Vegetation was sampled as described above.

Abiotic variables

Abiotic variables, canopy, and lower tree covers were sampled in 2007. These data were collected at three locations between the two perpendicular transects at the level of the first, fourth, and seventh plots (Fig. 2). The first set of environmental data was attributed to the two plots located in the ROW, the second one to the next three plots, and the third one to the last three plots of both transects (Fig. 2). We measured the water table level below the peat surface once at each location from hand excavated wells (measurements were made between the beginning of June and mid-August). Water table level can vary over the growing season, however, in the study area, June to mid-August corresponds to a period of relative stability in peatland surface water table following spring thaw and autumn rains (Girard et al. 2002; Whittington 2005; Rosa 2007). We therefore used this measure as a relative indication of site wetness. Water pH and electrical conductivity were measured in the field using an Orion 4-Star pH/conductivity meter (Thermo Electric Corporation, Bremen, Germany). Conductivity values were then adjusted to 25 °C and corrected for the concentration of hydrogen ions (Sjörs 1950). We also measured peat thickness with a metal probe inserted manually in the peat profile. Finally, we visually estimated the cover of canopy (>250 cm height) and lower (150 – 250 cm height) trees within a 10-m radius circular plot according to seven classes: 0%, <1%, 1%–10%, 11%–25%, 26%–50%, 51%–75%, and 76%–100%. Tree covers were used as indicators of shading.

Landscape variables

On each site we measured the width of the ROW. The years of construction of the ROW and of the last management treatment (selective cutting of the trees) in the ROW were obtained from Hydro-Québec, which generates, transmits, and distributes electricity in Québec. The extent of anthropogenic disturbances in the vicinity of each peatland was evaluated by estimating the percent area under human land use (agricultural fields, urban areas, roads, etc.) within a 2 km radius from the peatland centre using digital maps

(1 : 50 000) and ArcGIS™ 9.2 (Esri, Redlands, California). To determine if the immediate surrounding landscape type influenced the level of invasion, we identified the type of features (road, cultivated field, or forest) intersected by the ROW at the peatland margin. We also measured the distance between each peatland and the centre of the city of Montréal using Google Earth (Google Corporation, Menlo Park, California), because this city is the main area subject to exotic plant species invasion in the province (Jodoin et al. 2008). Finally, because the St. Lawrence River is one of the main dispersal vectors for exotic species in Québec (Delisle et al. 2003), we measured the distance at a right angle, between each peatland and this river, using Google Earth.

Data analyses

Prior to analyses, vascular plant species were sorted into three mutually exclusive groups: (i) native peatland species, (ii) native non-peatland species, and (iii) invasive species.² Species that occur always, preferably or frequently in open, semiforested, or wooded bogs or fens of Québec were classified as peatland species. Native species that are not normally observed in peatlands were classified as native non-peatland species. Exotic species and native species that have a competitive advantage after the disappearance of natural obstacles to their proliferation were classified as invasive species according to the definition of invasive species formulated by Valéry et al. (2008). We did not classify taxa for which we lacked adequate information on habitat preference ($n = 1$) or which we were not able to identify to the species level ($n = 15$). Furthermore, we did not classify non-vascular plants because of the lack of information available on habitat preference about most of the sampled species. Species habitat preference, origin, and invasiveness follow Lavoie and Saint-Louis (1999) and Tousignant et al. (2010 and cited references therein). In subsequent analyses, bogs and fens were always analysed separately. However, we did not classify species in terms of their peatland habitat preference (bog or fen) owing to the lack of information about several species. Statistical analyses were performed using JMP 7.0.1 (SAS Institute Inc., Cary, North Carolina) and version 2.3 of the R-language for statistics (R Development Core Team, Vienna, Austria).

Power line ROW transect

To assess whether power line ROWs act as dispersal vectors for invasive and native non-peatland species and, if so, to determine to which distance these species were able to penetrate within the ROWs, we tested whether their mean cover and their ratio to total vascular richness were comparable at different distances from the margin using analyses of variance (ANOVAs) followed by Tukey's post-hoc tests. Peatlands (blocks) were used as random effect. Rank transformations were used when needed to meet the assumptions of normality and homogeneity of variance. The mean covers of native non-peatland species and invasive species in each plot were obtained by averaging their total cover from the three circular subplots. Because the distance to the margin of the fourth, fifth, sixth, and seventh plots varied from site

² See supplementary Table S1 at <http://botany.nrc.ca>.

to site owing to the peatland area and because some plots were not sampled in small sites, posteriori distance classes were used. The plots in bogs were classified according to four categories of distance (0, 13, 31, and >50 m from the margin), and according to five categories for fens (0, 13, 31, 50–250, and >250 m from the margin). The first three distance classes correspond to the plots located at fixed distances. When more than one plot of a specific site could be assigned to a distance category, we used the mean of those plots to preserve only one datum per peatland per distance category.

Correlations were used to determine which abiotic and landscape variables favoured the invasion of native non-peatland and invasive species in ROWs. An overall measure of invasion for each site was estimated by summing the cover of all native non-peatland and invasive species in each subplot located in the ROWs and then averaging this cover per peatland. Abiotic variables sampled between the sixth and seventh plots of the power line ROW transects were used to characterize ROW conditions. Distances from Montréal and the St. Lawrence River variables were correlated to the cover of invasive species only, because native species are widespread in the study area and could not be associated to a specific site of introduction (e.g., Montréal) and because their dispersion does not involve a precise vector (e.g., St. Lawrence River). Pearson's correlations were performed when the assumption of normality was met; otherwise Spearman's correlations were performed. One bog was removed from correlation with the time elapsed since last management treatment variable because this data was unavailable. ANOVAs were performed on the nominal variable "type of feature intersecting the ROW" and rank transformations were performed for invasive species to meet the assumptions of normality and homogeneity of variances.

Perpendicular transects

To estimate the depth of edge influence of native non-peatland and invasive species at the peatland–ROW edge, we tested whether their mean cover and their ratio to total vascular richness were comparable at different distances from the edge of the ROW using ANOVAs followed by Dunnett's tests (using plots located in the ROW as controls). Peatlands (blocks) were used as random effect and the two transects were treated as replicates. The mean covers of native non-peatland and invasive species and their ratio to vascular richness were obtained as described above. Because Dunnett's test allows only one control site, we averaged data from the first and second plots (located in the ROW) for each transect, except for three bogs where only one plot was sampled. One fen was not used in these analyses because the last plots of both transects were disturbed by a major windfall. Rank transformations were used when needed to meet the assumptions of normality and homogeneity of variance. When normality was not obtained following these transformations, Friedman tests were performed instead of ANOVA.

To evaluate whether the peatland plant communities of adjacent habitats were affected by the presence of a ROW, we used Ward's hierarchical clusterings. When the existence of an edge is known, clustering techniques are more suitable to delineating boundaries than detection algorithms (McIntire and Fortin 2006). Ward's clustering technique was se-

lected because it allows the aggregation of sampling plots regardless of their spatial location. Only native peatland and nonvascular species were used for these analyses. Rare species (present in less than 5% of all circular subplots) were removed from the dataset. We then calculated the mean cover of each remaining species per distance class from the edge of the ROW using subplot data of each perpendicular transect. These mean covers were then standardized and used directly in the clustering. The two transects were treated as replicates. Following clustering, discriminant analyses were performed to identify indicator species that best discriminate between assemblages ($p < 0.05$) and to detect abiotic variables linked to each cluster. Mean values of cover classes for canopy and lower tree variables were used in discriminant analyses.

Results

A total of 405 taxa (294 vascular and 111 nonvascular) were recorded in the 34 sampled peatlands.² Among the vascular species, 156 are considered native peatland species, 83 native non-peatland species, and 39 invasive species. The most common species (according to the percentage of subplots in which they were sampled; Table 1) in ROWs intersecting a bog were *Chamaedaphne calyculata* (L.) Moench, *Ledum groenlandicum* Oeder, *Polytrichum strictum* Brid., *Kalmia angustifolia* L., and *Vaccinium oxycoccos* L. In bog expanse, they were *C. calyculata*, *K. angustifolia*, *V. oxycoccos*, *Kalmia polifolia* Wangenh., and *L. groenlandicum*. The most common species in ROWs intersecting a fen were: *Calamagrostis canadensis* (Michx.) Nutt., *Onoclea sensibilis* L., *Spiraea alba* Du Roi var. *latifolia* (Aiton) Dippel, *Impatiens capensis* Meerb., *Acer rubrum* L., *Lythrum salicaria* L., and *Typha* L. species. In the fen expanse, they were *A. rubrum*, *Trientalis borealis* Raf., *O. sensibilis*, *Maianthemum canadense* Desf., *Abies balsamea* L. (Mill.), and *Rubus pubescens* Raf.

Spread of native non-peatland and invasive species in power line ROWs

Bogs

The mean percent cover and the ratio to total vascular richness of both native non-peatland and invasive species decreased significantly from the margin toward the center (Fig. 3). Both groups of taxa were mostly restricted to the margin of the bog (<31 m from the margin). Within the first 31 m from the margin, invasive species, mainly *C. canadensis*, *Rubus setosus* Bigelow, and *Rubus idaeus* (Tables 1 and S1²), were on average five times more abundant than native non-peatland species, although both groups represented roughly the same proportion of the total vascular flora throughout the ROW (Fig. 3).

The cover of native non-peatland and of invasive species was not significantly correlated to any of the variables tested (Table 2). ANOVAs on the kind of features intersecting the ROW at the bog margin revealed no effect on the level of invasion (native non-peatland species: $F = 1.6700$, $p = 0.2123$; invasive species: $F = 0.0129$, $p = 0.9872$).

Fens

The mean percent cover and the ratio to total vascular richness of native non-peatland species were similar along

Table 1. Dominant plant species (sampled in >10% of the subplots) found in the 23 bogs and 11 fens each intersected by a power line right-of-way (ROW) in southern Québec.

	% of subplots in which species was observed			
	Bogs		Fens	
	ROW transects	Peatland expanse	ROW transects	Peatland expanse
Peatland species				
<i>Abies balsamea</i> L. (Mill.)	1.3	3.7	0.5	28.5
<i>Acer rubrum</i> L.	13.6	9.2	25.4	78.5
<i>Alnus incana</i> (L.) Moench ssp. <i>rugosa</i> (Du Roi) R.T. Clausen		2.4	9.9	19.5
<i>Andromeda polifolia</i> L. var. <i>glaucophylla</i> (Link) DC	11.3	23.4		
<i>Aralia nudicaulis</i> L.				10.8
<i>Carex aquatilis</i> Wahlenb.	12.2	1.3	0.9	
<i>Carex oligosperma</i> Michx.	20.7	35.6		
<i>Chamaedaphne calyculata</i> (L.) Moench	46.9	75.0	1.4	0.5
<i>Coptis trifolia</i> (L.) Salisb.	0.7	1.3	0.5	15.9
<i>Cornus sericea</i> L. ssp. <i>sericea</i>				10.3
<i>Dryopteris carthusiana</i> (Vill.) H.P. Fuchs	2.4	0.1	2.3	11.2
<i>Eriophorum vaginatum</i> L. var. <i>spissum</i> (Fernald) Boivin	17.1	18.4		
<i>Eriophorum virginicum</i> L.	5.6	11.1		0.3
<i>Eupatoriadelphus maculatus</i> (L.) King & Rob. var. <i>maculatus</i>	0.7		13.1	2.6
<i>Galium palustre</i> L.	0.7		10.3	3.1
<i>Ilex mucronata</i> (L.) Powell, Savolainen & Andrews	9.6	10.3	0.5	11.0
<i>Ilex verticillata</i> (L.) A. Gray	1.8	1.3	2.8	16.2
<i>Kalmia angustifolia</i> L.	40.2	62.4		2.6
<i>Kalmia polifolia</i> Wangenh.	29.3	53.7		
<i>Larix laricina</i> (Du Roi) K. Koch	17.6	27.8	2.8	9.2
<i>Ledum groenlandicum</i> Oeder	44.7	48.6		1.5
<i>Maianthemum canadense</i> Desf.	3.1	2.7	8.0	29.2
<i>Maianthemum trifolium</i> (L.) Sloboda	16.4	22.3	2.8	0.3
<i>Onoclea sensibilis</i> L.	4.2		38.0	31.3
<i>Osmunda cinnamomea</i> L.	0.9	0.2	7.0	25.9
<i>Osmunda regalis</i> L. var. <i>spectabilis</i> (Willd.) A. Gray	0.7	0.2	6.6	14.1
<i>Oxalis montana</i> Raf.			10.3	0.5
<i>Photinia melanocarpa</i> (Michx.) K.R. Robertson & Phipps	18.2	9.7	1.4	1.8
<i>Picea mariana</i> (Mill.) Britt.	2.4	16.4		2.6
<i>Rhododendron canadense</i> (L.) Torr.	8.7	13.9		0.8
<i>Rubus pubescens</i> Raf.	1.6		8.0	27.4
<i>Spiraea alba</i> Du Roi var. <i>latifolia</i> (Aiton) Dippel	17.5	2.1	37.1	4.6
<i>Symplocarpus foetidus</i> (L.) Salisb. ex Nutt.			10.3	2.8
<i>Thuja occidentalis</i> L.		0.1	0.9	14.6
<i>Triadenum fraseri</i> (Spach) Gleason	1.3	0.2	11.7	1.5
<i>Trientalis borealis</i> Raf.	5.1	3.8	2.8	36.2
<i>Vaccinium angustifolium</i> Ait.	13.6	21.3		3.3
<i>Vaccinium oxycoccos</i> L.	37.3	55.4		
Native non-peatland species				
<i>Salix petiolaris</i> Sm.	0.2	0.4	10.8	1.0
<i>Solidago canadensis</i> L.	3.3		13.6	3.1
<i>Solidago rugosa</i> Mill.	3.1		15.5	4.1
<i>Thalictrum pubescens</i> Pursh			13.1	8.9
<i>Thelypteris palustris</i> Schott var. <i>pubescens</i> (Lawson) Fernald	1.3	0.1	19.2	3.6
<i>Typha</i> L. spp. (<i>angustifolia</i> , <i>latifolia</i>)	1.3	1.2	21.6	0.5
Invasive species				
<i>Betula populifolia</i> Marsh.	5.6	2.3	8.5	17.2
<i>Calamagrostis canadensis</i> (Michx.) Nutt.	18.7	1.9	44.1	6.2
<i>Clematis virginiana</i> L.	0.7		16.0	6.7
<i>Impatiens capensis</i> Meerb.	0.2		27.2	17.7
<i>Lythrum salicaria</i> L.			21.1	3.8
<i>Phragmites australis</i> (Cav.) Trin. ex Steud.		1.1	12.7	0.5
<i>Rubus setosus</i> Bigelow	13.8	0.1	5.2	1.0

Table 1 (concluded).

	% of subplots in which species was observed			
	Bogs		Fens	
	ROW transects	Peatland expanse	ROW transects	Peatland expanse
Nonvascular species				
<i>Aulacomnium palustre</i> (Hedw.) SchwAgr.	8.0	2.5	14.1	8.7
<i>Brachythecium</i> Schimp. spp.	1.3	0.1	12.2	20.3
<i>Plagiothecium denticulatum</i> (Hedw.) Schimp.	0.9	0.1	3.8	15.4
<i>Polytrichum strictum</i> Brid.	41.1	38.9	2.8	
<i>Pseudobryum cinclidioides</i> (HA1/4b.) T. Kop.				10.3
<i>Sphagnum angustifolium</i> (Jensen ex Russow) Jensen	23.6	28.9	14.6	6.2
<i>Sphagnum capillifolium</i> (Ehrh.) Hedw.	14.2	24.5	0.9	1.0
<i>Sphagnum centrale</i> Jensen	1.3	1.5	4.2	11.0
<i>Sphagnum fallax</i> (Klinggr.) Klinggr.	24.9	29.8	7.5	2.8
<i>Sphagnum fimbriatum</i> Wilson var. <i>fimbriatum</i>	1.1	1.8	2.8	12.3
<i>Sphagnum fuscum</i> (Schimp.) Klinggr.	12.2	24.3	1.4	0.3
<i>Sphagnum girgensohnii</i> Russow	3.1	0.7	7.5	14.1
<i>Sphagnum magellanicum</i> Brid.	30.9	41.8	4.2	3.3
<i>Sphagnum rubellum</i> Wilson	28.2	45.6		
<i>Sphagnum squarrosum</i> Crome	0.7	0.2	10.3	13.8

Note: Peatland expanses represent data from perpendicular transects excluding plots located in ROWs.

the ROW (Fig. 3). On average, native non-peatland species covered between 10% and 20% and represented one third of the total richness in each plot. This group of species was mainly characterized by *Typha* spp., *Thelypteris palustris* Schott var. *pubescens* (Lawson) Fernald, and *Solidago rugosa* Mill. (Table 1). The mean percent cover of invasive species, mostly represented by *C. canadensis*, *I. capensis*, *L. salicaria*, and *Clematis virginiana* L. (Table 1) was about twice that of native non-peatland species, although they represented roughly the same proportion of total vascular richness (Fig. 3). Yet, the mean percent cover and ratio to richness of invasive species were similar only along the first 250 m of the ROW and declined significantly after this distance, even though some invasive species were still present farther from the margin.

The cover of native non-peatland species was significantly and positively correlated with water conductivity and pH, whereas it was negatively correlated with water table level (Table 2). A low water level was also associated with a high cover of invasive species (Table 2). As for bogs, ANOVAs on the kind of features intersecting the ROW at the fen margin revealed no effect on the level of invasion (native non-peatland species: $F = 0.1275$, $p = 0.8823$; invasive species: $F = 2.1104$, $p = 0.1918$).

Spread of native non-peatland and invasive species in peatland expanse

Bogs

The mean percent cover of native non-peatland and invasive species was very low on all plots (<5%) and always represented a minor proportion (<2%) of species richness (Fig. 4). No significant difference was found in the mean percent cover and the ratio to total vascular richness for both native non-peatland and invasive species between the ROW and the peatland expanse (Fig. 4).

Fens

The mean percent cover and the ratio to total vascular richness of native non-peatland species were significantly greater in the ROW than in the fen expanse (Fig. 4). However, these species still made up more than 10% of the plant assemblages in the plots farthest from the ROW edge (Fig. 4). We did not detect any significant difference in the cover of invasive species between the ROW and the peatland expanse (Fig. 4). Invasive species, mainly *I. capensis*, *Betula populifolia* Marsh., *R. idaeus*, and *C. virginiana* (Table 1) were in fact more efficient than the native non-peatland species in colonizing the peatland expanse, with a total mean cover in each plot ranging between 10% and 15%, even at 43 m from the ROW. No significant difference was detected in the ratio of invasive species to total richness between the ROW and the first plot located in the peatland expanse (Fig. 4), but this ratio showed significant differences between the ROW and the plots located at ≥ 4 m from the edge.

Impacts of ROWs on native peatland and nonvascular species

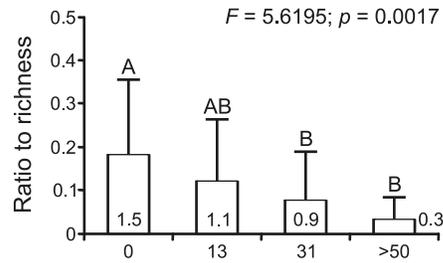
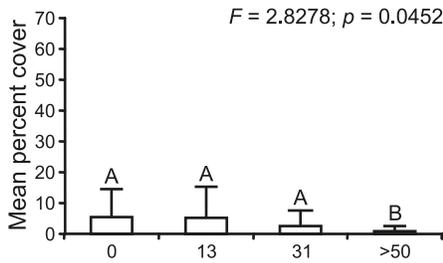
Bogs

Cluster analysis performed using peatland vascular species first separated the ROW plots (plots 1 and 2) from those of the bog expanse (plots 3–8; Fig. 5). The second split separated the plots within 9 m from the edge (plots 3–5) from those at ≥ 17 m from the edge (plots 6–8). Tree species (*A. balsamea*, *A. rubrum*, and *P. mariana*) and the ericaceous species *Andromeda polifolia* L. var. *glaucophylla* (Link) DC were indicator species for the bog expanse. Indicator species at the ROW edge were *C. calyculata* and *Maianthemum trifolium* (L.) Sloboda, while *K. angustifolia* was the only indicator species of the plots located farther from the edge. Discriminant analysis performed on environmental variables showed that only the cover of canopy

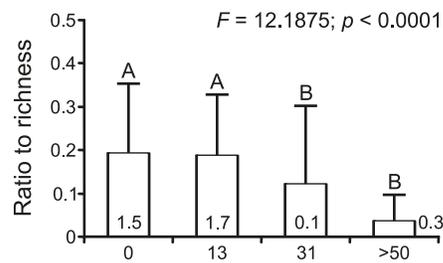
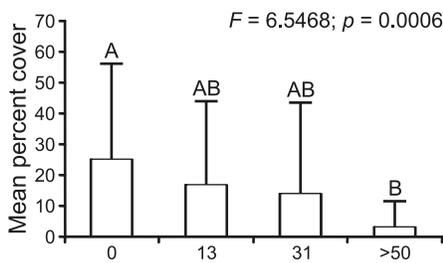
Fig. 3. Mean percent cover of vascular native non-peatland and invasive species and their ratio to total vascular richness as a function of distance from the margin in the power line right-of-way transect in bogs ($n = 23$) and fens ($n = 11$). For each graphic of ratio to richness, the mean number of native non-peatland species or invasive species are indicated in columns for each category of distance. Different letters indicate a significant difference at $\alpha = 0.05$ as determined by a Tukey's test. Bars indicate standard deviation.

Bogs

Native non-peatland species

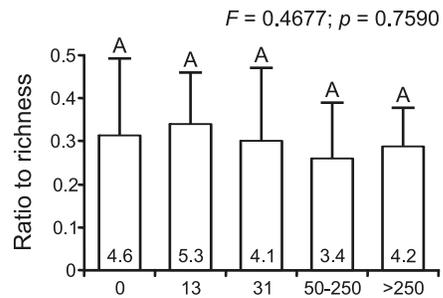
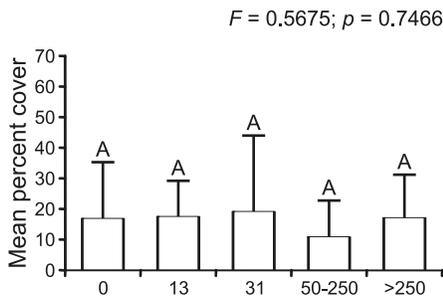


Invasive species

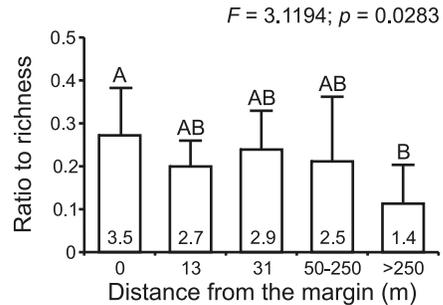
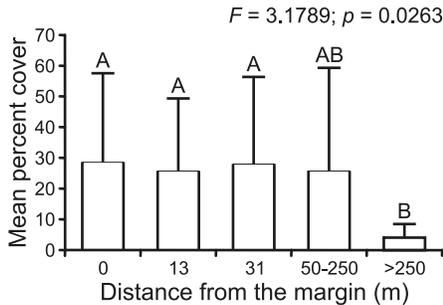


Fens

Native non-peatland species



Invasive species



($p < 0.0001$) and lower tree ($p = 0.002$) variables were significantly different between the three groups. Tree layers had higher covers in the peatland expanse than in the ROW. Nonvascular plants did not show any trend in the clustering (results not shown).

Fens

The first and second divisions of cluster analysis using native vascular peatland species in fens were similar to those of bogs; first separating the ROW plots (plots 1 and 2) from those of the peatland expanse (plots 3–8), and then,

Table 2. Pearson's (a) and Spearman's (b) coefficients of correlation between the cover of native non-peatland and invasive species and environmental and landscape variables in the power line ROW transect of bogs ($n = 23$; time elapse since last maintenance treatment, $n = 22$) and fens ($n = 11$).

Variables	Bogs		Fens	
	Native non-peatland	Invasive	Native non-peatland	Invasive
Anthropogenic disturbances (%)	0.40 ^b	-0.04 ^b	0.09 ^b	0.13 ^b
Distance from Montréal (km)	na	0.03 ^b	na	0.02 ^a
Distance from St. Lawrence River (km)	na	0.11 ^b	na	-0.17 ^b
Peat thickness (cm)	-0.04 ^b	-0.02 ^b	0.38 ^b	-0.27 ^a
ROW width (m)	-0.23 ^b	-0.25 ^b	-0.18 ^b	0.01 ^a
Time elapsed since construction (years)	0.23 ^b	0.20 ^b	-0.42 ^b	-0.19 ^b
Time elapsed since last maintenance treatment (years)	-0.38 ^b	0.34 ^b	0.43 ^b	-0.01 ^b
Water corrected conductivity ($\mu\text{S}/\text{cm}$)	0.30 ^b	0.11 ^b	0.80 ^{b**}	0.41 ^b
Water table level (cm)	0.05 ^b	0.02 ^b	-0.64 ^{b**}	-0.72 ^{b*}
Water pH	0.29 ^b	0.05 ^b	0.65 ^{b*}	0.23 ^a

Note: * $p < 0.05$, ** $p < 0.01$.

plots within 9 m from the edge (plots 3–5) from those greater than 17 m from the edge (plots 6–8) (Fig. 5). Indicator species in the ROW were shade intolerant plants, represented by *S. alba* var. *latifolia* and *Triadenum fraseri* (Spach) Gleason, while shade tolerant and tree species (*A. rubrum*, *Arisaema triphyllum* (L.) Schott. ssp. *triphyllum*, *Carex trisperma* Dewey, *Clintonia borealis* Aiton (Raf.), and *Thuja occidentalis* L.) were indicative of the peatland expanse. Innermost plots were characterized by species associated with forest interiors such as *Linnaea borealis* L. and *Osmunda cinnamomea* L. Among environmental variables sampled, only the covers of canopy and lower trees differed significantly between the three clusters ($p < 0.0001$ for both variables). As in bogs, they occupied a higher cover in peatland expanse than in the ROW. Cluster analysis performed using nonvascular plants only separated the ROW plots (plots 1 and 2) from those of the peatland expanse (plots 3–8). *Polytrichum commune* Hedw. var. *commune* and *Sphagnum fallax* (Klinggr.) Klinggr. were indicative species of the ROW. *Plagiothecium denticulatum* (Hedw.) Schwägr. and *Sphagnum girgensohnii* Russow, two forest species, were indicative of the peatland expanse. Discriminant analyses performed on environmental variables among the two clusters revealed that the covers of canopy and lower trees were both significantly higher ($p < 0.0001$ for both variables) in the peatland expanse than in the ROW.

Discussion

Our results showed that power line ROWs are efficient dispersal vectors and favour the spread of native non-peatland and invasive plant species in peatlands, mostly for fens. In the latter, invasive species were found in abundance along the first 250 m within the ROWs. Native non-peatlands species were less abundant but were able to colonize in the entire ROW areas. Invasive species present in the ROWs were also able to colonize the adjacent fen habitats. Although they were mostly concentrated in the first 4 m from the ROW edges, some species were able to establish at more than 43 m of the ROWs. Conversely, the impact of power line ROWs on bogs seems to be minor

because both types of species were infrequent in the ROWs and in the expanses of this type of peatland, except at the margins.

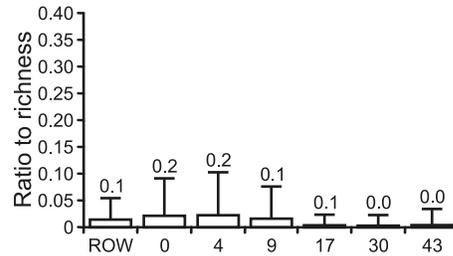
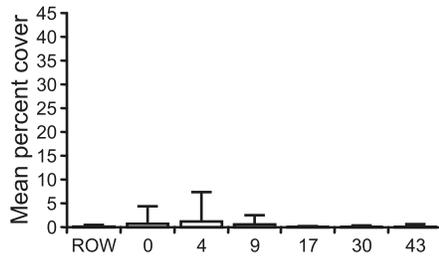
Although, ROWs seem efficient dispersal vectors in peatlands, our results are to some extent contrary to what we hypothesized since the cover of native non-peatland and invasive species in ROWs decreased rapidly within the first 50 m from the margin in bogs. This result likely highlights the fact that nutrient-poor, acidic soils are inhospitable habitats for nonombrotrophic species, even after disturbance. In fens, native non-peatland species were able to colonize the ROWs at every distance from the margin but invasive species decreased sharply after 250 m, which was unexpected. More detailed investigations are needed to explain this trend.

The different response of bogs and fens in regard to native non-peatland and invasive species invasion in power line ROWs is likely linked in part to their intrinsic edaphic setting. Bogs are characterized by very low water and soil pH, corrected conductivity, and nutrient content (e.g., Sjörs 1950; Zoltai and Vitt 1995). These harsh characteristics only allow the colonization and growth of a limited number of specialist species (Hájek et al. 2007). On the other hand, fens receive runoff water enriched by the surrounding mineral soils and are characterized by higher water and soil pH ranges and corrected conductivity (e.g., Sjörs 1950; Gorham and Janssens 1992), which may be more suitable conditions for the establishment and spread of native non-peatland and invasive species. Furthermore, invasive species were restricted to the margin in bogs, where there is usually an enrichment of soil (Damman and Dowhan 1981). Similar results were obtained in urban wetlands of New Jersey, where exotic species were more abundant on sites with higher pH and nutrient content (Ehrenfeld 2008). Harsh edaphic conditions have also been identified as a limiting factor for plant invasion in other ecosystems (e.g., D'Antonio 1993; Harrison 1999; Larson et al. 2001). For example, it has been demonstrated that Californian serpentine grasslands are resistant to invasion, primarily owing to their low soil nutrient content, especially nitrogen and phosphorus (Huenneke et al. 1990; Harrison 1999).

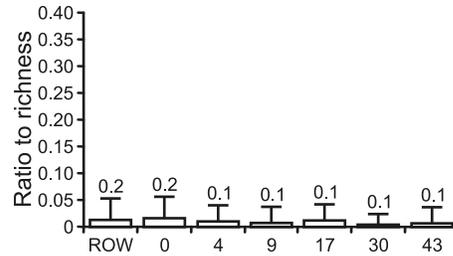
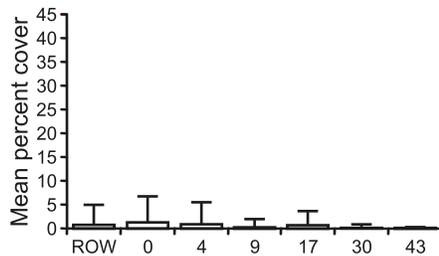
Fig. 4. Mean percent cover of vascular native non-peatland and invasive species and their ratio to total vascular richness in the perpendicular transects as a function of distance from the right-of-way (ROW) edge in bogs ($n = 23$) and fens ($n = 10$). For each graphic of ratio to richness, the mean numbers of native non-peatland species or invasive species are indicated in columns for each category of distance. Asterisks indicates a significant difference from ROW plot at $\alpha = 0.05$ as determined by Dunnett's test. Bars indicate standard deviation.

Bogs

Native non-peatland species

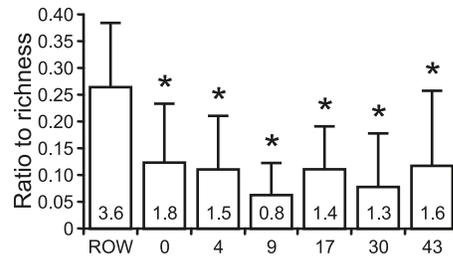
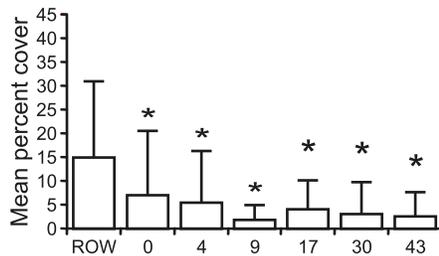


Invasive species

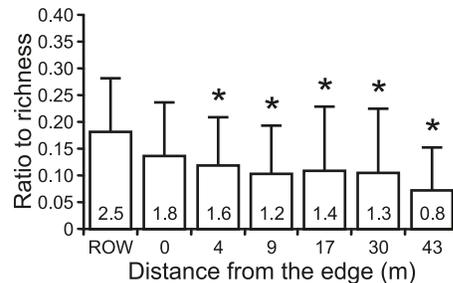
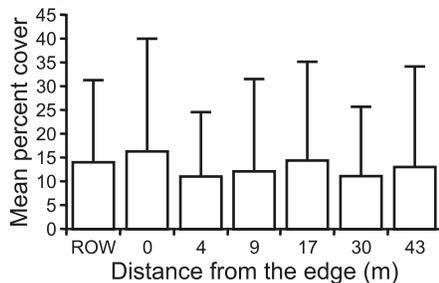


Fens

Native non-peatland species



Invasive species

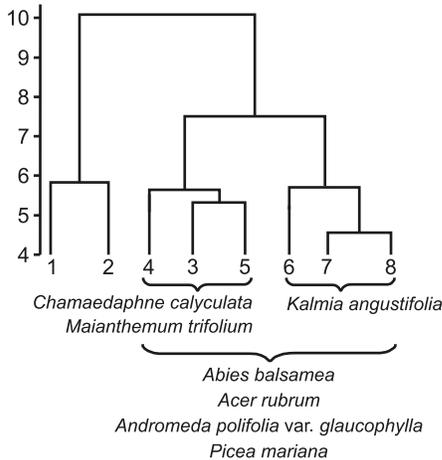


The opening of the forest canopy for the construction of power line ROWs may also have exacerbated the susceptibility of peatlands to invasion, especially in fens because most of the sampled bogs were already open habitats. The increase in light, the reduction of barriers for wind-dispersed seeds, and the diminution of competition following the clearing of high-growing species have already been shown to favour the establishment of invasive and herbaceous pioneer species (Gholz et al. 1985; MacLellan and Stewart

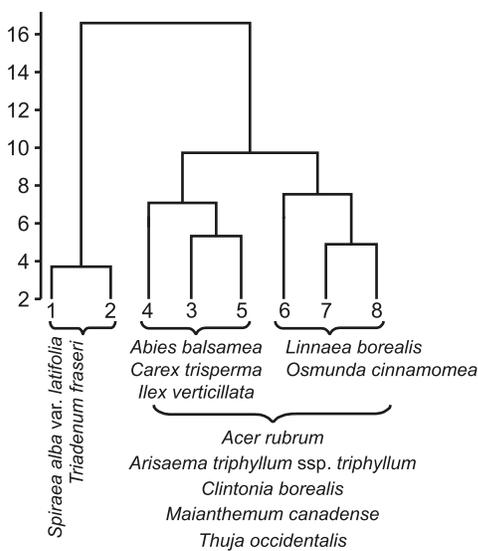
1986; Parendes and Jones 2000; Rubino et al. 2002). Moreover, the increased sun exposure following a clearcut usually results in increased soil temperature, which, in conjunction with the remaining tree residues, accelerates decomposition and leads to greater nutrient availability (Hannerz and Hånnell 1997; Locky and Bayley 2007). In our study, the intact canopies of the fen habitats adjacent to the ROWs seem to have prevented strong colonization of the peatland expanse by native non-peatland species from the ROWs, even though

Fig. 5. Ward's dendrograms using native vascular peatlands species in bogs ($n = 23$) and fens ($n = 11$) and nonvascular species in fens. Numbers under each branch indicate the plot number on the perpendicular transects (see Fig. 2). Indicator species ($p < 0.05$) are listed under each cluster.

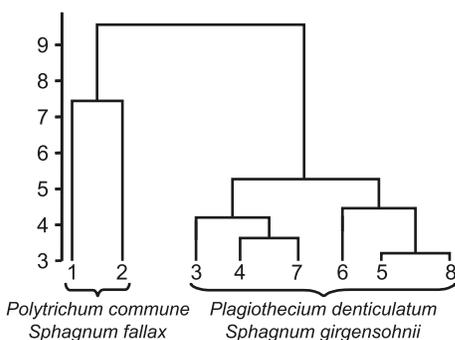
Bogs: vascular species



Fens: vascular species



Fens: non-vascular species



the broad environmental tolerance of some invasive species allowed them to penetrate the adjacent fen (Fig. 4). However, the impact of power line ROWs seems to be notably reduced at distances farther than 4 m from the edge, because

the ratio of invasive species to total richness was lower at this distance in the peatland expanse compared with the ROW and only a limited number of invasive species could penetrate the peatland expanse.

Not only may light intensity have favoured encroachment by native non-peatland and invasive species in ROWs and to some extent in peatland expanses, it may have also exacerbated the difference in peatland species composition between the ROWs and the adjacent peatlands for both bogs and fens. Herbaceous heliophilous low-stature species (e.g., *S. alba* var. *latifolia*, *T. fraseri*) were indicative of the ROW in fens, whereas forest trees and shade-tolerant herbaceous species (e.g., *A. balsamea*, *A. rubrum*, *C. borealis*, *P. mariana*) were representative of the expanse of both bogs and fens. The presence of *A. rubrum* as an indicator species in bogs is somewhat surprising, but this species was only found in the expanse of the two wooded bogs and may be related to past disturbances such as logging (Tousignant et al. 2010). Indicator nonvascular species in fens were also clearly associated to the shade gradient from the ROW to the peatland expanse (Fig. 5). The replacement of late successional nonvascular species by early successional ones (e.g., genus *Polytrichum*) is indeed a well-known phenomenon that can occur between 1 and 8 years following clear-cutting in peatlands (Hannerz and Hånell 1997; Locky and Bayley 2007), which is less than the period of time since the establishment of most power line ROWs in our study (>25 years).

The differential invasion response observed between bogs and fens could also be explained in part by the theory on niche saturation stipulating that occupied resource space decreases the probability of successful establishment of new species (Palmer and Maurer 1997). Sampled bogs were characterized by a widespread *Sphagnum* mat creating a continuous ground layer, whereas nonvascular species were scattered and led to a disrupted ground cover in sampled wooded fens. Bare soils in fens may have favoured the germination of seeds transported by wind from the surrounding landscape (Pykälä 2004). Although *Sphagnum* mats are good germination beds for tree seeds (Ohlson and Zackrisson 1992; Hörnberg et al. 1997), seedlings that establish are usually overgrown by *Sphagnum* (Ohlson and Zackrisson 1992). Ecological niches occupied by *Sphagnum* mosses may thus be an additional limiting factor for the establishment of native non-peatland and invasive species in bogs.

Finally, while the surrounding landscape has been shown to influence the susceptibility of several wetlands to invasion (Findlay and Houlahan 1997; Findlay and Bourdages 2000; Maheu-Giroux and de Blois 2007; Bowman Cutway and Ehrenfeld 2009), we found no effect of the landscape on the level of invasion of peatland intersected by power line ROWs. The low influence of our landscape variables is likely because of the relatively homogenous landscape in the study area. Surprisingly, time elapsed since the power line construction or the last maintenance treatment in ROWs does not seem to influence the degree of invasion of a peatland, meaning that young and old ROWs support approximately the same cover of native non-peatland and invasive species. We thus suppose that by the time we surveyed the vegetation (usually more than 25 years after construction) these species had time to establish in each ROW.

Conclusion

Because native non-peatland and invasive species showed a rapid decline along ROWs in open or semiforested bogs, power line ROWs are likely not a threat to bog vegetation, at least in temperate regions. In those regions, few mesic and xeric species are adapted to waterlogged, nutrient-poor, acidic conditions and thus surrounding landscape likely represents a natural barrier for the spread of non-peatland or invasive species in bogs. In regions where environmental conditions of mesic and xeric sites are much more similar to those found in bogs, such as in boreal regions, we may have found a greater impact of ROWs on bogs, especially for native non-peatland species. On the other hand, ROWs located in wooded fens supported a considerable cover of native non-peatland and invasive species and some of those species, mainly invasive ones, could spread into the adjacent peatland to more than 43 m from the edge. The presence of those species in ROWs is worrying, since we can expect that they would be able to extend their coverage within adjacent habitats if additional natural or anthropogenic disturbances were to occur near the ROW. Thus, efforts should be undertaken to avoid disturbances in adjacent habitats in a way to confine native non-peatland and invasive species within ROWs. This is especially important since we likely underestimated the impacts of ROWs on adjacent habitats owing to the fact that our perpendicular transects were located in the centre of the peatland where potential invaders coming from the ROWs were the less abundant.

Acknowledgments

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