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RESEARCH ARTICLE

Neighboring edges: Interacting edge effects from linear disturbances in treed fens

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Abstract

Questions: Edge influence on forest biodiversity is an important environmental effect associated with habitat fragmentation, but extrapolating the influence of edges across the broader landscape has been difficult, especially for situations where multiple edges exist in close proximity. We asked whether there were differences in edge effects between two types (3 m vs 8 m width) of low-severity linear disturbance (seismic lines) and whether there were interactions of edge effects when seismic lines occur in dense networks; that is, do multiple narrow seismic lines have a stronger or weaker edge influence than a single narrow seismic line.

Location: Treed peatlands in northeastern Alberta, Canada.

Methods: Seismic lines are created during oil and gas exploration and are responsible for dissection of boreal forests in western Canada. We sampled vascular plants along transects perpendicular to seismic lines in moderate-rich and poor treed fens. We used the "Randomization Test of Edge Influence" (RTEI) to calculate the magnitude and distance of edge effects and then compared these between narrower (3 m) versus wider (8 m) lines and between single narrow lines versus multiple narrow lines (parallel and ~50 m apart).

Results: In moderate-rich fens, we found a positive edge influence on understorey diversity from both wide and narrow seismic lines. We also found a weakening edge interaction on diversity, that is, single narrow seismic lines had a stronger edge influence on diversity than did multiple narrow seismic lines. In treed poor fens, multiple narrow seismic lines had a negative edge effect on tree density, understorey abundance, richness, and composition. In addition, we found strengthening edge interactions in treed poor fens on tree density, graminoid cover, and understorey composition.

Conclusions: Even narrow linear disturbances, such as seismic lines, can have significant edge effects and these are exacerbated when lines occur in dense networks.

KEYWORDS
boreal, cumulative impacts, edge influence, edge interaction, plants, seismic lines, treed peatlands, understorey vegetation

1 | INTRODUCTION

Edge influence, also called edge effects, are the ecological changes that occur at the interface of a forest patch and the adjacent non-forested area. It can be a major driver of changes in forest structure and is associated with forest fragmentation (Fahrig, 2003). In the boreal forest, linear disturbances are one of the main causes of forest dissection as they are widespread and can be found at high densities. For example, in western Canada, seismic lines — linear corridors of cleared forests (approx. 3–8 m wide) used for oil and gas exploration (Dabros et al., 2018; Lee & Boutin, 2006) — can be found at densities as high as 40 km/km^2 in some areas and edge effects are estimated to dominate the region despite the actual disturbance footprint making up only 6% of the region (Riva & Nielsen, 2021).

Edge influence can be quantified using two components: magnitude of edge influence (MEI) and distance of edge influence (DEI). MEI describes how much a parameter at the edge differs from values at the interior forest, while DEI describes how far a significant difference between edge and interior forest extends from the edge into the forest (Harper et al., 2005). In the boreal forest, the extent of edge influence is typically less than in temperate and tropical forests. This has been attributed to the shorter canopy height, inherent heterogeneity of forest types and canopy cover, and frequent natural disturbances (Harper et al., 2015).

Though edge effects are well studied, extrapolating their influence across landscapes has been limited by knowledge gaps in edge ecology, including a paucity of studies on how multiple edges interact (Porensky & Young, 2013; Ries et al., 2004, 2017). In the boreal forest, Harper et al. (2007) examined the interaction of edge influences of large openings — i.e., harvest blocks and lakes — but little else has been done. Here, we take advantage of the boreal landscape in western Canada, which is highly dissected due to seismic lines, to examine interactions of edge influence from the dense network of narrow, low-severity disturbances.

There are two types of seismic lines: conventional seismic lines and low-impact seismic lines. Historically, conventional seismic lines were created by using bulldozers to clear vegetation and were spaced at approximately 300–500 m apart (Dabros et al., 2018). These conventional seismic lines (approximately 4–12 m wide) are now increasingly being replaced with low-impact seismic lines, to mitigate the environmental impacts of oil exploration in the boreal forest. Low-impact seismic lines are narrower, approximately 3 m wide, and involve lighter equipment, thus resulting in less soil disturbance (Dabros et al., 2018). The canopy opening created by seismic lines leads to higher light intensity, higher air temperature, and lower relative humidity at the edge of the seismic lines compared to in the forest interior (Franklin et al., 2021). Despite being quite narrow, low-impact seismic lines have been shown to exhibit edge influence on understorey vegetation (Dabros et al., 2017; MacFarlane, 2003). In addition, low-impact seismic lines are placed at a much higher density (50–100 m apart) than conventional lines (Dabros et al., 2018); this could lead to a larger overall impact on the remaining forest than conventional seismic lines that, although wider, are more spaced out. In this study, we explore how edge influence changes when two lines are in proximity to each other compared to situations of single edges that are more commonly studied.

The first objective was to compare the edge influence of conventional seismic lines (hereafter referred to as “wide” seismic lines) versus low-impact seismic lines (hereafter referred to as “narrow” seismic lines). We focused on the edge influence on understorey vegetation in treed peatlands, as seismic lines in these ecosites are particularly long-lasting (van Rensen et al., 2015) and peatlands dominate large parts of northern Alberta (~65% of the oil-sands region). Wide seismic lines have stronger changes in abiotic conditions, for example higher light intensity and air temperatures, and a higher DEI on microclimatic conditions than narrow seismic lines (Franklin et al., 2021; Stern et al., 2018). We thus expected wide seismic lines to have a higher DEI on vegetation compared to narrow seismic lines. Our second objective was to determine if there is an interaction of edge influence when two narrow seismic lines are in close proximity. There are three possible outcomes when multiple edges are present: (i) no edge interaction; that is the presence of a second edge does not alter the edge influence of a single edge, (ii) strengthening interaction, the presence of a second edge strengthens the edge influence of a single edge, and (iii) weakening interaction, the presence of a second edge weakens the edge influence of a single edge (Harper et al., 2007; Porensky & Young, 2013). We expected a strengthening interaction on vegetation abundance because increased light availability from the higher density of linear disturbances would promote an even stronger increase in vegetation abundance. However, we expected a weakening or no edge interaction on plant diversity. This is based on an expectation of higher species richness and diversity at edges as disturbance-adapted species are able to establish near the edge as an added component to the existing “interior” community (Ries et al., 2017). We expected that a higher density of edges would change conditions in the forest to the point where they are no longer suitable for “interior” species, thus leading to losses in interior species. This would counter any increase in species richness and diversity associated with the ingress of edge-adapted species, leading to a weakening edge interaction on plant diversity (i.e. when there are multiple edges, diversity at the edge is similar to that in the interior). Concomitantly, we expected a shift in species composition characterized by increasing abundance of edge-adapted species and reduced abundance of “interior” species throughout the forest patches between the closely-spaced seismic lines.

2 | METHODS

This study was conducted in treed peatlands approximately 50 km south of Fort McMurray, Alberta, Canada (56°23′4.32″ N, 111°35′13.52″ W). Mean annual temperature in the region is 1°C with an average annual precipitation of 418.6 mm (Environment & Climate Change, 2013; from nearby meteorological station: Fort McMurray). Overstorey trees were dominated by black spruce (*Picea mariana*) or tamarack (*Larix laricina*) or a mixture of both. These are relatively short-statured and open forests; average tree height was 6.4 m and average canopy cover was 57.1%.

Sampled seismic lines were created 12 (eight lines) or 17 years (five lines) before sampling (in 2005 or 2000). The seismic lines still had not developed any overstorey trees at the time of sampling. Seismic lines ranged in width from 4 to 12 m for conventional wide seismic lines and 1.5 to 3 m wide for low-impact narrow seismic lines. Seismic lines in the area were created in a grid and were not managed or purposely maintained in any way after creation; however, they are occasionally disturbed by off-highway-vehicle travel, which can contribute to their slow recovery. Sites were classified as poor fens, or moderate-rich fens based on the vegetation at the site, using Beckingham and Archibald's (1996) ecosite classification guide for Northern Alberta. Moderate-rich fens were characterized by higher *Carex* and *Salix* diversity and abundance, while poor fens were dominated primarily by ericaceous shrubs such as *Vaccinium vitis-idaea* and *Ledum groenlandicum*. Sampling occurred from late June to mid-August 2017.

We established multiple transects from a seismic line into the adjacent treed peatland for each of three treatments: (i) "single wide" seismic line into the adjacent treed peatland ($n = 5$ in moderate-rich fens, $n = 7$ in poor fens), (ii) "single narrow" seismic line into the adjacent treed peatland ($n = 6$ in moderate-rich fens, $n = 5$ in poor fens), and (iii) "multiple narrow", from a narrow seismic line to the nearest parallel narrow seismic line ($n = 14$ for both peatland types) (Appendix S1). Since seismic lines extend over long distances (tens of kilometers), there were a limited number of available seismic lines in treed fens that were adjacent to undisturbed treed peatland, especially narrow seismic lines that are clustered. Thus, for all line types, a given seismic line may have multiple transects (Appendix S1), but all were at least 100 m apart. Transects were also established to be at least 100 m from any other large disturbance (i.e., other wide seismic lines, well pads, or roads). Sampled seismic lines were oriented either N–S or E–W. For the E–W seismic lines, transects always went north of the seismic line (i.e., edge aspect was south-facing), while transects on N–S seismic lines always went west of the seismic line (edge aspect was east-facing). Transect orientation was kept consistent to minimize variation in edge influence due to differences in edge direction (orientation). These orientations were selected based on what was available in the sampling area, that is narrow seismic lines in the sampling area were always south or west of the adjacent undisturbed treed peatland.

For the single wide and single narrow treatments, sampling locations were established at 1, 2.5, 5, 10, 15, 20, 25, 35, 50, and 75 m from the edge of the seismic line into the forest, with plots centered on these locations (Appendix S2). For the multiple narrow treatment, sampling points were established at 1, 2.5, 5, 10, 15, 25 m from the edge of both the starting and ending seismic line. Further distances were not considered since some seismic-line spacing was only 50 m. In one multiple narrow transect, the distance between the two seismic lines was too small to allow for even a 25 m sampling location. To characterize vegetation on the seismic lines, two sampling points were established 1.4 m apart on the line and to either side of the starting point of each transect.

At each sampling location, cover of each species of understorey vascular plant was visually estimated in 1-m^2 circular plots. Nomenclature follows Moss (1983; Appendix S3). Canopy cover was estimated at the center of each plot using a convex spherical densiometer; measurements were made in each of the four cardinal directions and values averaged.

Tree density and tree basal area were measured in plots (2 m × 4 m), with the long axis of these plots perpendicular to the edge. These plots were large enough to capture variation in tree density as trees on the site tended to be small (average tree diameter at 1.3 m height [DBH] was 3.15 cm and average tree density was 13 trees per plot, with trees defined as woody species with DBH >1 cm). For the single wide and single narrow treatments these tree plots were placed along the transect at 0–4 m, 4–8 m, 8–12 m, 13–17 m, 23–27 m, 33–37 m, 48–52 m, and 73–77 m from the seismic line. For the multiple narrow treatment, tree plots were placed along the transect at 0–4 m, 4–8 m, 8–12 m, 13–17 m, and 23–27 m from each seismic line. Thus the 1- and 2.5-m sampling locations for vascular understorey vegetation were located within the same tree plot. Within each tree plot, we recorded the DBH and species of all trees (anything with DBH > 1 cm) and calculated tree basal area and tree density for each plot.

2.1 | Statistical analysis

Understorey response variables of interest were species richness (^0D), the exponential of Shannon entropy (hereafter referred to as ^1D), the inverse of the Gini–Simpson index (hereafter referred to as ^2D), short-shrub cover (<1 m tall; excluding tree species), forb cover, graminoid cover, and community composition. Hill numbers were used for diversity (^1D and ^2D), as they are in units of effective number of species (Hill, 1973; Jost, 2006). Overstorey response variables were total tree density and tree basal area. The two site types (poor fen, moderate-rich fen) were analyzed separately since preliminary analysis showed that they responded differently. To characterize seismic-line conditions, we compared understorey abundance, diversity, and composition on wide and narrow seismic lines to the reference "interior" conditions, using the "Randomization Test of Edge Influence" (RTEI) Excel program (Harper & Macdonald, 2011; $\alpha = 0.10$). For this analysis, we combined the seismic-line plots from both the single narrow and multiple narrow treatments.

Distance and magnitude of edge influence were determined by running the RTEI analyses for each treatment separately. MEI is calculated as $(\bar{e} - \bar{i})/(\bar{e} + \bar{i})$, where $\bar{e}$ is the average value at a given distance from the edge and $\bar{i}$ is the average value for the interior reference sites (Harper & Macdonald, 2011). For all analyses, the plots 75 m from the single narrow and single wide treatments were used as reference interior plots; thus, edge effects for each treatment were quantified using the same reference interior dataset. We used the 75-m plots as representative of "interior" treed fen conditions because it has been shown that edge influence on vegetation in Canadian boreal forests rarely extends past 20 m with the maximum observed DEI reaching 60 m (Harper et al., 2015). In addition, it is difficult to ensure a consistent site type and avoid other disturbances beyond 75 m. Significant edge influence was indicated by two or more consecutive (or separated by one distance) significant MEIs ($\alpha = 0.10$). We chose this alpha level to minimize the risk of missing an edge influence due to low power after splitting transect data by peatland type. To test the edge influence on community composition, we first conducted non-metric multidimensional scaling (NMDS) analyses. For the NMDS, we excluded species that occurred in less than 5% of the plots for a given site type. We then ran the RTEI analyses on the NMDS coordinates (axes 1 and 2). Following initial results for edge effects on diversity in the treed moderate-rich fen site type, we undertook additional analyses to explore edge influence on the cover of the 11 most dominant species: *Ledum groenlandicum*, *Smilacina trifolia*, *Rubus chamaemorus*, *Picea mariana* (<1 m tall), *Betula pumila* (<1 m tall), *Salix planifolia*, *Vaccinium vitis-idaea*, *Oxycoccus microcarpus*, *Carex aquatilis*, *Salix pedicellaris*, and *Larix laricina* (<1 m tall). We did not test the edge interaction (see below) on the cover of dominant species as we only examined these variables to help further explain the diversity trends we found. Since there were no significant edge effects on diversity in treed poor fens, we did not test the edge influence on individual species cover in poor fens.

For variables exhibiting an edge influence in either the single narrow or multiple narrow treatments, we tested for the presence of an edge interaction by using Welch's *t*-test to compare the average values of a response variable between these two treatments at each distance separately ($\alpha = 0.05$). No significant differences between the two treatments indicated no edge interaction. We define a strengthening edge interaction as when the difference between the multiple narrow treatment and interior reference sites is greater than the difference between the single narrow treatment and interior sites, for example if both treatments have a positive edge influence and the average value at a given distance is higher at the multiple narrow treatment than at the single narrow treatment. In contrast, a weakening edge interaction is when the difference between the multiple narrow treatment and interior reference sites is less than the difference between the single narrow treatment and reference sites. When necessary, data were $\log_{10}$-transformed to ensure normality prior to analysis by Welch's *t*-test (NMDS first axis and tree density). The graminoid cover data could not be fully normalized; therefore, these data were $\log_{10}$-transformed, to ensure homogeneity of variance, and then analyzed using the non-parametric Wilcoxon rank sum test.

3 | RESULTS

3.1 | Vegetation characteristics of seismic lines

In both peatland types, wide seismic lines tended to have greater differences in understorey cover and diversity as compared to the reference interior than did narrow seismic lines, although there were notable differences for both types of seismic lines (Table 1). For both poor fens and moderate-rich fens, canopy cover was, as expected, significantly lower on both the narrow and wide seismic lines than in the reference interior treed fen (Table 1). In addition, for both site types graminoid cover was significantly higher on the wide seismic lines compared to the reference interior, but did not differ between narrow seismic lines and the reference (Table 1). In poor fens, short-shrub cover on both wide and narrow seismic lines was significantly higher than in the interior treed fens (Table 1). In moderate-rich fens, only wide seismic lines had higher short-shrub cover than the reference fen, while narrow seismic lines did not differ from the reference (Table 1). In poor fens, species richness and diversity (both ^1D and ^2D) were significantly higher on wide seismic lines compared to the reference fen, while narrow seismic lines did not differ from the reference (Table 1). In moderate-rich fens, both wide and narrow seismic lines had significantly higher species richness and ^1D than the reference fen (Table 1). In contrast, ^2D in moderate-rich fens was significantly higher on narrow seismic lines compared to the reference fen, but did not differ between wide seismic lines and the interior fen (Table 1). Community composition on wide seismic lines was also significantly different from the interior treed fen for both peatland types (based on scores on axis 1 and/or 2 of the NMDS), but did not differ between narrow seismic lines and the interior fen (Table 1). In both peatland types, total understorey cover and forb cover did not differ between either wide or narrow seismic lines and the reference interior fen (Table 1).

3.2 | Edge influence from wide and narrow seismic lines

As expected, edge effects were minimal for the single narrow seismic-line treatment. In moderate-rich fens, the single narrow treatment had a significant positive edge influence on ^1D from the seismic line to 2.5 m from the edge and from 15 to 25 m from the edge (Figure 1b, Appendices S4 and S5). The single narrow treatment also had a significant positive edge influence on ^2D from 15 to 25 m from the edge (Figure 1c, Appendices S4 and S5). Similarly, the single wide treatment in moderate-rich fens had a significant positive edge influence on species richness (DEI = 5–20 m), and diversity (*D* [DEI = 1–50 m], ^2D [DEI =5–35 m]; Figure 1, Appendices S4 and S5). There was no significant edge influence on species richness for single narrow seismic lines (Appendices S4 and S5).

In moderate-rich fens, both the single narrow and single wide treatments had a significant positive edge influence on the cover of *Salix planifolia* (Figure 2, Appendices S6 and S7). For the single narrow treatment, DEI was from 5 to 20 m, while for the single wide treatment, DEI was from 2.5 to 20 m (Figure 2, Appendices S6 and S7). The single narrow treatment also had a significant positive edge influence on *Smilacina trifolia* (DEI = 1–25 m) and a negative edge influence on *Rubus chamaemorus* (DEI = 1–5 m; Figure 2, Appendices S6 and S7). There was no significant edge influence for either the single wide or single narrow treatments in moderate-rich fens for any other variables (Figure 2, Appendices S4 and S6).

TABLE 1 Comparisons of vegetation variables (means and in parentheses standard errors) on narrow and wide seismic lines and reference "interior" treed fen sites for poor and moderate-rich fens. Significant differences between the seismic line and the reference (as determined by a significant magnitude of edge influence) is indicated in bold for $p < 0.1$ or in bold and italicized for $p < 0.05$

	Poor fens			Moderate-rich fens		
Response variable	**Wide SL**	**Narrow SL**	**Reference**	**Wide SL**	**Narrow SL**	**Reference**
Canopy cover (%)	***23.00 (3.22)***	***32.53 (2.30)***	61.39 (5.26)	***24.12 (4.31)***	***34.12 (2.77)***	58.82 (6.09)
Understorey cover (%)	33.95 (1.97)	33.67 (2.95)	29.29 (2.99)	38.41 (2.39)	34.50 (2.19)	29.01 (5.69)
Forb cover (%)	13.97 (0.89)	12.22 (1.11)	12.88 (2.12)	14.56 (1.78)	14.73 (1.38)	13.73 (3.65)
Graminoid cover (%)	***2.79 (0.47)***	0.68 (0.17)	0.58 (0.16)	***5.05 (0.56)***	2.94 (0.56)	1.92 (0.55)
Short-shrub cover (%)	**15.86 (2.33)**	***19.99 (3.32)***	10.25 (1.49)	***18.25 (1.60)***	15.88 (2.21)	10.91 (2.09)
Species richness (no. of species/m^2)	***14.07 (0.74)***	8.30 (0.44)	8.50 (0.99)	***16.50 (1.42)***	**12.23 (0.80)**	9.82 (0.96)
^1D (effective no. of species/m^2)[a]	***7.92 (0.96)***	4.54 (0.40)	4.88 (0.65)	***8.23 (0.61)***	**7.39 (0.58)**	5.64 (0.48)
^2D (effective no. of species/m^2)[a]	**5.85 (0.87)**	3.46 (0.33)	3.77 (0.55)	5.34 (0.39)	**5.71 (0.45)**	4.28 (0.42)
NMDS 1	***−0.57 (0.09)***	−0.10 (0.09)	−0.18 (0.16)	***−0.56 (0.10)***	−0.09 (0.11)	0.07 (0.15)
NMDS 2	−0.11 (0.15)	0.04 (0.07)	−0.14 (0.11)	***−0.15 (0.09)***	−0.07 (0.07)	0.16 (0.12)

[a] ^1D is the exponential of Shannon's entropy and ^2D is the inverse of the Gini–Simpson index (Jost, 2006).

In poor fens, the only significant edge influence at the single narrow treatment was on community composition, with DEI from 25 to 50 m (Appendices S8 and S9). There was no significant edge influence for the single wide treatment for any variables (Appendix S8).

3.3 | Interaction of edge influence

For multiple narrow lines in moderate-rich fens, we found a significant negative edge influence on the cover of *Salix pedicellaris* (DEI = 5–15 m) and *Larix laricina* (<1 m tall; DEI = 1–25 m; Figure 2, Appendices S6 and S7). The multiple narrow treatment did not have significant edge influence on any other variables (Appendices S4 and S6). Because there was a significant edge influence on diversity (^1D and ^2D) for the single narrow treatment, we tested for interaction of edge effects by comparing average values between the single narrow and multiple narrow. We found a weakening edge interaction at 15 m for both ^1D and ^2D, that is the average values for the single narrow treatment were higher than for the multiple narrow treatment, and for the reference site (Table 2, Figure 1).

In contrast, we found a strengthening edge interaction on both the overstorey and understorey in treed poor fens. The multiple narrow treatment had a significant positive edge influence on tree density, up to 27 m from the edge (Appendices S8 and S9), with a significant strengthening edge interaction at 17 and 27 m (Table 2, Figure 3). The multiple narrow treatment also had a significant edge influence on understorey composition, from 1 to 25 m from the edge (Appendices S8 and S9). For understorey composition, there was a significant strengthening edge interaction 5 m from the edge (Table 2). The multiple narrow treatment had a significant negative edge influence on species richness (DEI = 5–25 m), understorey cover (DEI = 2.5–15 m), forb cover (DEI = 2.5–25 m), and graminoid cover (DEI = 1–25 m; Figures 3 and 4, Appendices S8 and S9). There was a strengthening edge interaction on graminoid cover at 1, 5, and 15 m from the edge (Figure 4, Table 2). In contrast, understorey cover, forb cover, and species richness did not show significant differences between the multiple narrow and single narrow treatments for any distance; this suggests there were no interactions of edge influence for those variables (Table 2). There was no significant edge influence on the other variables from the multiple narrow treatments (Appendix S8).

4 | DISCUSSION

Seismic lines were characterized by having lower canopy cover, higher short-shrub and graminoid cover, and higher vascular plant diversity compared to the interior treed fens. Despite the continued open conditions found on seismic lines 12–17 years after their creation, edge effects into adjacent fens in the poor fen type where quite limited, regardless of line width (wide or narrow). We only observed edge influence on community composition for single narrow seismic lines in poor fens. In contrast, moderate-rich fens had positive edge influences on richness and diversity for single seismic lines regardless of line width (wide and/or narrow). As expected, depth of edge influence was higher for single wide seismic lines, up to 50 m from the edge, compared to single narrow seismic lines, where edge influence was limited to 25 m from the edge. In contrast to our results, Dabros et al. (2017) found that in upland, black spruce–lodgepole pine (*Pinus contorta* var. *contorta*)-dominated stands, narrow seismic lines had a negative and shallower edge influence on herbaceous plant diversity (DEI = 15 m) and cover (DEI = 5 m). This contrast may be due to differences in site type and in time since disturbance: they sampled three years after seismic-line creation while we sampled lines more than 10 years after creation of seismic lines that remained open.

Increased diversity was likely a response to increased resource availability from the seismic-line opening (Ries et al., 2004, 2017).

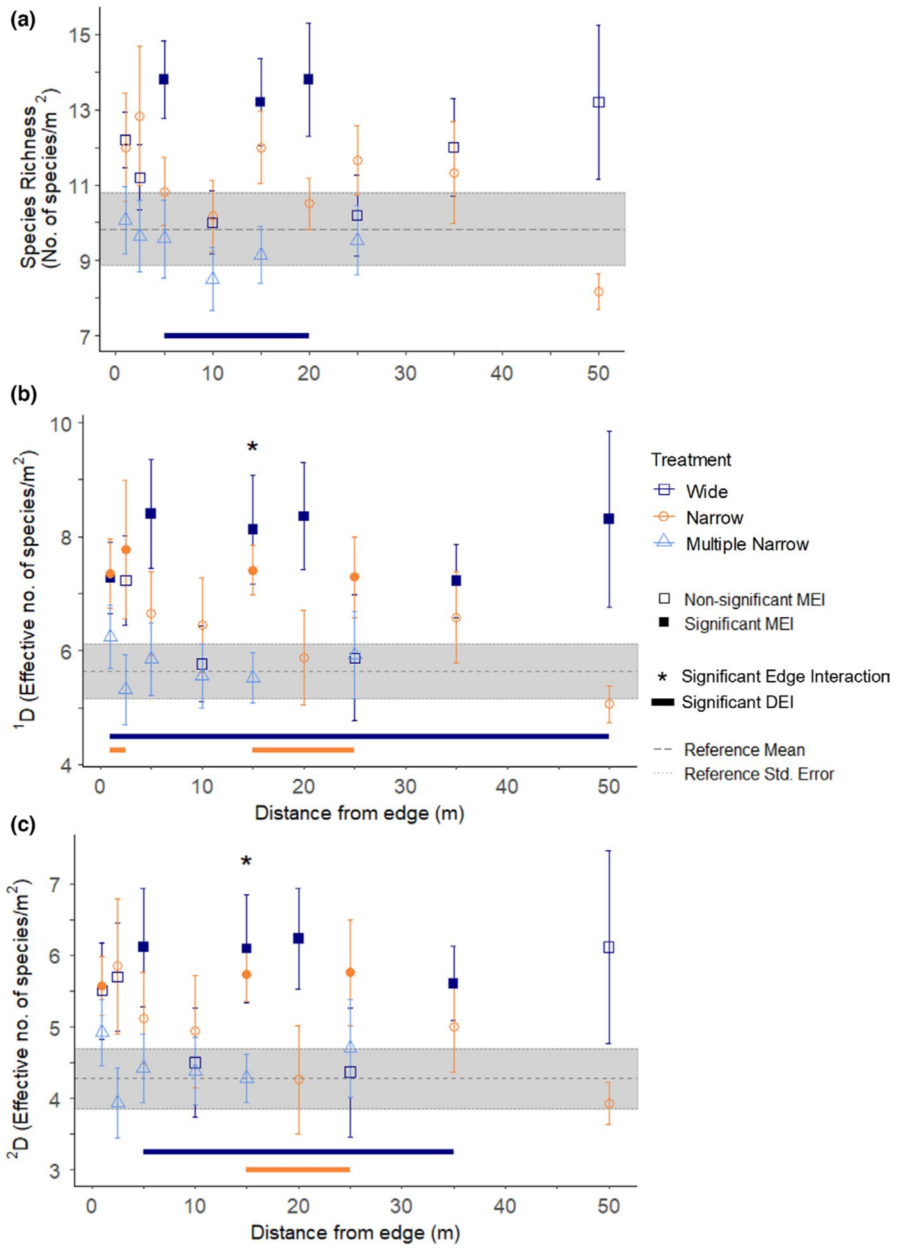

FIGURE 1 Edge effects from seismic lines in moderate-rich treed fens. Given are average values for: (a) species richness (no. of species/m^2), (b) ^1D (effective no. of species/m^2), and (c) ^2D (effective no. of species/m^2) at each distance from the seismic line into the interior fen for the three treatments. ^1D is the exponential of Shannon's entropy and ^2D is the inverse of the Gini–Simpson index (Jost, 2006). Error bars represent standard error of the mean. The horizontal dashed line represents the average value for the interior treed fens, with the standard error represented by the shaded grey area. Filled symbols indicate significant magnitude of edge influence (MEI; $\alpha = 0.1$) and the solid horizontal line at the bottom indicates the distances over which there was a significant distance of edge influence (color-coded by treatment) (see also Appendices S4 and S5). Asterisks represent a significant difference between the multiple narrow and single narrow treatments for that distance, indicating a significant edge interaction (see Table 2)

Specifically, the seismic-line opening could increase abundance of edge-adapted species that would be favored by increased light (Dawe et al., 2017; Franklin et al., 2021; Stern et al., 2018) or increased pollinators (Nelson et al., 2021; Riva et al., 2018, 2020), and likely seed dispersers. However, this could also lead to shade-tolerant or interior species being outcompeted at the edge of the seismic line; we found evidence of this in that *Rubus chamaemorus* had lower abundance at the edge of the single narrow treatment. Thus, the highest species diversity was found ~5 to 25 m from the edge of seismic lines; this is most likely where both edge-associated and interior species could coexist. Our analysis of the dominant species showed *Salix planifolia* and *Smilacina trifolia* — generalist fen species — increased at the edges of seismic lines. Finnegan et al. (2018) also found higher *Salix* spp. abundance on wide seismic lines in treed wetlands in western Alberta's foothills boreal forests, while Dabros et al. (2017) found that *Rubus chamaemorus* cover was lower at the edge of narrow seismic lines in upland black spruce–lodgepole pine-dominated stands.

The limited edge influence on overstorey and understorey abundance for both single narrow and single wide seismic lines was unsurprising due to the narrow nature of seismic-line openings, the low patch contrast between these openings and the adjacent forest, and the inherent heterogeneity in treed peatlands. Our findings support Harper et al.'s (2005) hypotheses that reduced patch contrast and a heterogeneous landscape will lead to lower magnitude and DEI. Treed peatlands are characterized by a shorter canopy height (~8–10 m) and sparser tree cover than upland forest types (Coops et al., 2016; Guo et al., 2017; Mao et al., 2019), which results in a low patch contrast between the seismic line and the adjacent undisturbed peatland. In addition, treed peatlands here are interspersed with graminoid- and shrub-dominated fens, which lack an overstorey of trees. Thus, the seismic lines are similar to tree-less fens and the

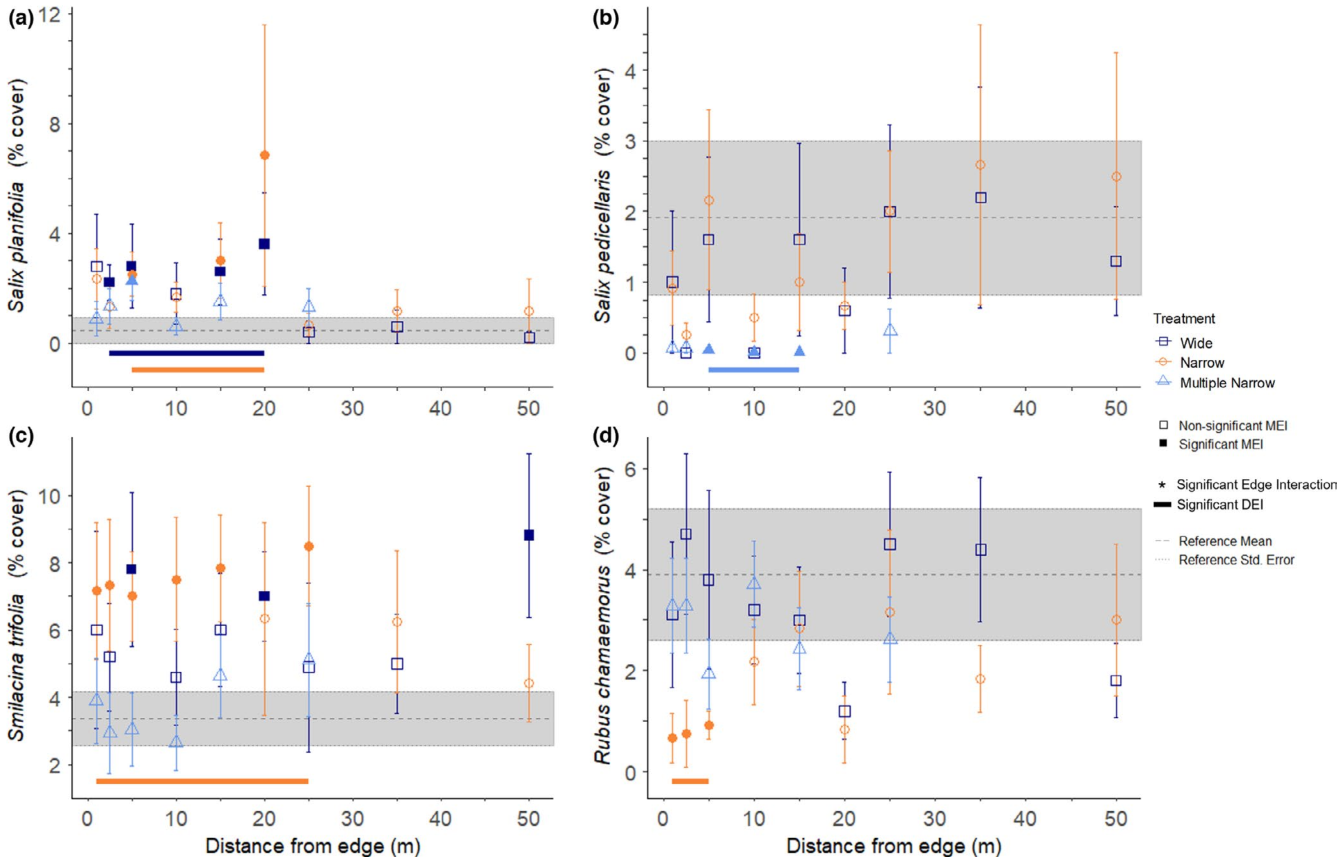

FIGURE 2 Edge effects from seismic lines in moderate-rich treed fens. Given are average cover values for: (a) *Salix planifolia*, (b) *Salix pedicellaris*, (c) *Smilacina trifolia*, and (d) *Rubus chamaemorus* at each distance from the seismic line into the interior fen for the three treatments. Error bars represent standard error of the mean. The horizontal dashed line represents the average value for the interior treed fens, with the standard error represented by the shaded grey area. Filled symbols indicate significant magnitude of edge influence (MEI; $\alpha = 0.1$) and the solid horizontal line at the bottom indicates the distances over which there was a significant distance of edge influence (color-coded by treatment) (see also Appendices S6 and S7)

plant communities we studied are either adapted to both habitats or to canopy openings. In drier black spruce forest stands, Harper et al. (2016) found that edge influence from harvesting decreased over time, with edge influence on forest structure and understorey composition only extending 5 m into the adjacent forest, 16 years after harvest (but see Dupuch & Fortin, 2013 for edge expansion 60 years after harvest). Based on this, it is unsurprising that we found limited edge influence from a much smaller disturbance.

4.1 | Edge interaction

In moderate-rich fens, multiple narrow seismic lines had a negative edge influence only on *Salix pedicellaris* and *Larix laricina* abundance, up to 25 m from the edge. In poor treed fens, multiple narrow seismic lines had a positive edge influence on tree density, negative edge influence on total understorey cover, forb, and graminoid cover, and species richness. As expected, changes in understorey cover and richness also led to an edge influence on community composition. DEI on forb and graminoid cover, species richness, understorey composition, and tree density extended up to 25 m from the edge, and to 15 m for total understorey cover. As expected, we found an edge interaction for multiple narrow seismic lines. In moderate-rich fens we found a weakening edge interaction on diversity at 15 m from the edge, while in poor treed fens we found a strengthening edge interaction for tree density (i.e., compared to both the reference forest and the single narrow treatment, the multiple narrow had higher tree density, from 13 to 27 m from the edge), graminoid cover (1, 5 and 15 m from the edge), and understorey composition (5 m from the edge).

The increase in conifer tree density at the edge of the multiple narrow seismic lines in treed poor fens would have resulted in lower light availability than in the reference interior, which in turn might explain the observed negative edge influence on understorey, forb, and graminoid cover, species richness and the edge influence on community composition. Similarly, in upland coniferous stands, Dabros et al. (2017) found light availability was lowest 5 m from a single narrow seismic line and herbaceous cover was reduced 2–5 m from the seismic line; they attribute this to observed (but unquantified) increased tree canopy cover at the edge of the seismic line. However, we found multiple narrow seismic lines had a greater distance of edge influence on understorey cover (DEI to 15 m), forb and graminoid cover, species richness, and composition (DEI to 25 m) in treed poor fens than Dabros et al. (2017) found for single narrow seismic lines in upland stands.

We hypothesize that the increase in tree density at the edge is due to increased layering by the surrounding black spruce trees. Studies on regeneration following strip clear-cutting have found increased production of black spruce layers post harvest, driven by increased soil temperature and reduced competition from shrubs and parent trees (Pothier, 2000; Prévost & Dumais, 2018). We may be seeing the same effect in seismic lines, which have been shown to have higher soil and air temperatures than in adjacent forests (Dabros et al., 2017; Franklin et al., 2021). It is possible that the removal of trees and increase in resource availability associated with construction of a single narrow seismic line failed to trigger a strong response in vegetative growth, but proximity to multiple seismic lines stimulated a significant increase in black spruce layering.

It is also possible that the area between multiple narrow seismic lines may be experiencing a surface drying effect, which the single seismic lines may not have; this could explain the strengthening edge interaction on tree density in poor fens. This drying effect, coupled with increased light availability at the edge, may create

TABLE 2 Results of edge interaction tests

	Distance from the edge of the seismic line					
	1 m	2.5 m	5 m	10 m	15 m	25 m
(A) Understorey in moderate-rich fens						
^1D (effective no. of species/m^2)[c]						
t-Statistic	1.33	1.78			**3.05**	1.32
df	13.26	7.69			**14.54**	15.03
p-Value	0.21	0.11			**0.008**	0.207
^2D (effective no. of species/m^2)[a]						
t-Statistic					**2.86**	1.05
df					**12.87**	13.24
p-Value					**0.014**	0.31
(B) Understorey in poor fens						
NMDS first axis						
t-Statistic		−0.77	−1.02[a]	−1.04	−0.051	−1.53
df		6.16	4.40	6.27	4.76	5.86
p-Value		0.47	0.36	0.34	0.96	0.18
NMDS second axis						
t-Statistic	−1.92	−1.23	**−2.78**			
df	7.16	5.72	**8.78**			
p-Value	0.10	0.27	**0.02**			
Understorey cover (%)						
t-Statistic		1.29	1.41		1.06	
df		4.43	4.37		5.39	
p-Value		0.26	0.23		0.33	
Forb cover (%)						
t-Statistic		1.22	1.70	1.22	0.66	1.12
df		5.31	5.46	4.17	6.67	4.11
p-Value		0.27	0.14	0.29	0.53	0.32
Graminoid cover (%)						
W statistic[b]	**54**[a]	43[a]	**60**[a]	46[a]	**52**[a]	50[a]
p-Value	**0.0547**	0.40	**0.008**	0.17	**0.047**	0.12
Species richness (no. of species/m^2)						
t-Statistic			1.16	1.20		1.58
df			4.71	5.68		6.53
p-Value			0.30	0.28		0.16

TABLE 2 (Continued)

	Distance from the edge of the seismic line				
	4 m	8 m	12 m	17 m	27 m
(C) Overstorey in poor fens					
Tree density (No. of trees/ha)					
t-Statistic	−2.21[a]	−1.36a	−1.72	−2.48	−3.07
df	5.99	8.47	9.64	10.21	16.98
p-Value	0.07	0.21	0.12	0.03	0.007

Edge interaction was evaluated by comparing average values at a given distance between the single narrow and multiple narrow treatments (α = 0.05) for the following variables (based on significant edge effects for either treatment – see Appendices S4 and S8): (A) diversity (^1D and ^2D) in moderate-rich fens; (B) community composition, understorey cover, forb cover, graminoid cover, species richness in poor fens; and (C) tree density in poor fens. For moderate-rich fens, single narrow treatments had a positive edge influence on diversity and multiple narrow treatments had no edge influence on diversity; thus, significant differences between the two treatments would indicate a weakening edge interaction (i.e., the difference between the multiple narrow treatment and interior reference sites is less than the difference between the single narrow treatment and reference sites). In contrast, in poor fens, multiple narrow treatments had a negative edge influence on these variables and there was no edge influence from single narrow treatments; thus, significant differences between the two treatments would indicate a strengthening edge interaction (i.e., the multiple narrow treatment was more different from the reference than the single narrow treatment was). Bolded values indicate significant differences between the two treatments (α = 0.05).

[a]Log_{10}-transformation was applied to ensure conformation to the assumption of normality.

[b]The data could not be normalized so a Wilcoxon test was used to compare the two treatments and log_{10}-transformation was applied to ensure homogeneity of variances.

[c]^1D is the exponential of Shannon's entropy and ^2D is the inverse of the Gini–Simpson index (Jost, 2006).

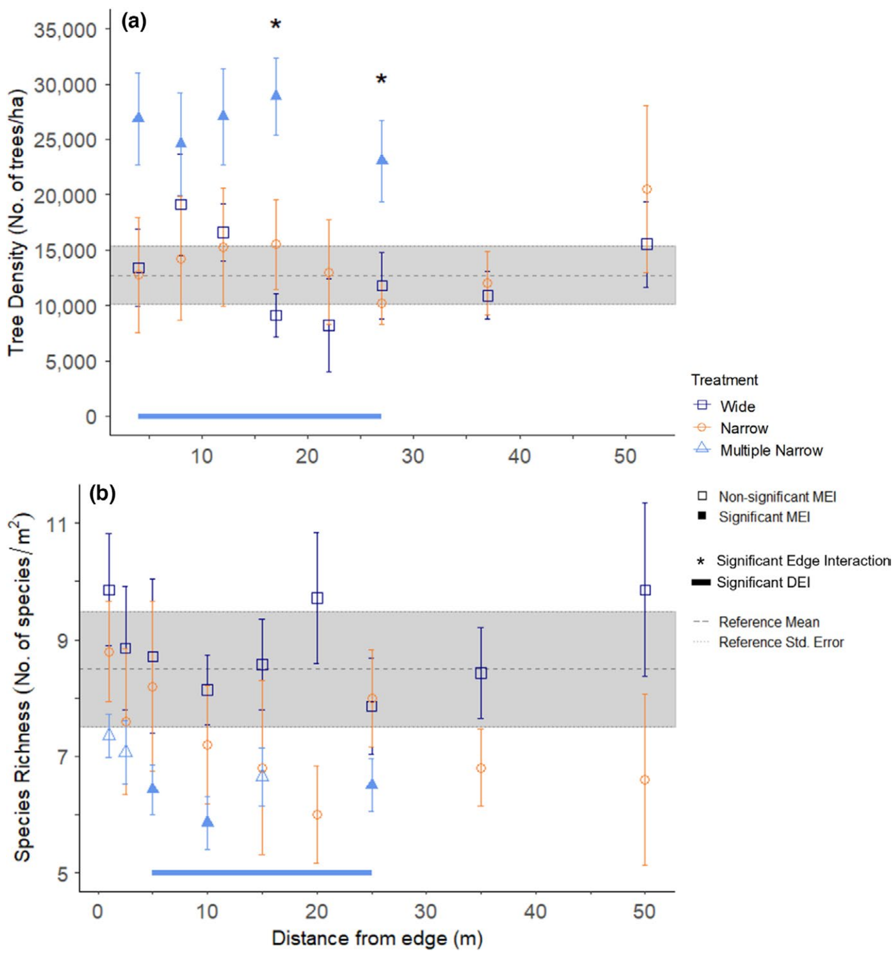

FIGURE 3 Edge effects from seismic lines in poor treed fens. Given are average values for: (a) tree density (no. of trees/ha) and (b) species richness (no. of species/m^2) at each distance from the seismic line into the interior fen for the three treatment types. Error bars represent standard error of the mean. The horizontal dashed line represents the average value for the interior treed fens, with the standard error represented by the shaded grey area. Filled symbols indicate significant magnitude of edge influence (MEI, α = 0.1) and the horizontal solid line at the bottom indicates the distances over which there was significant depth of edge influence, color-coded by treatment (see also Appendices S8 and S9). Asterisks represent a significant difference between the multiple narrow and single narrow treatments for that distance, indicating a significant edge interaction (see Table 2)

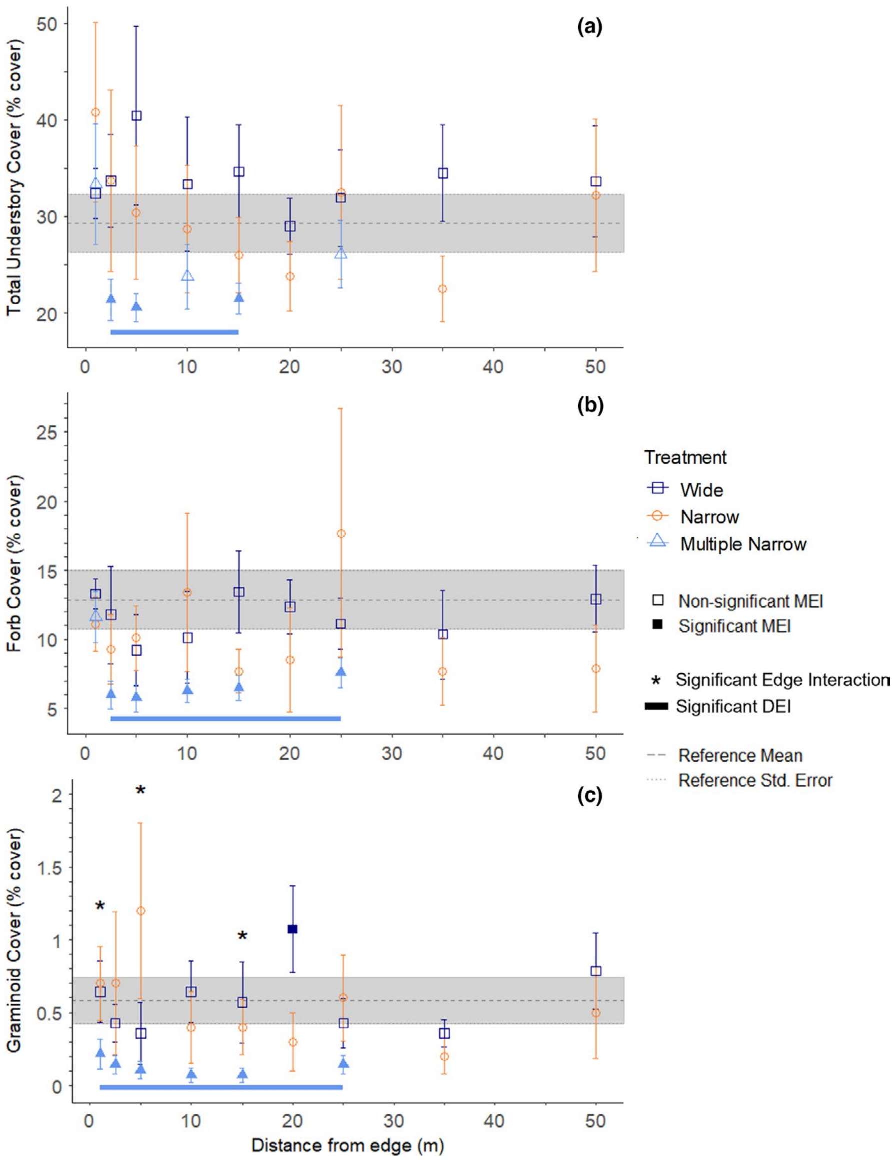

FIGURE 4 Edge effects from seismic lines in in poor treed fens. Given are average values for: (a) total understorey cover (% cover), (b) forb cover (% cover), and (c) graminoid cover (% cover) at each distance from the seismic line into the interior fen for the three treatment types. Error bars represent standard error of the mean. The horizontal dashed line represents the average value for the interior treed fens, with the standard error represented by the shaded grey area. Filled symbols indicate significant magnitude of edge influence (MEI, $\alpha = 0.1$) and the horizontal solid line at the bottom indicates the distances over which there was significant depth of edge influence, color-coded by treatment (see also Appendices S8 and S9). Asterisks represent a significant difference between the multiple narrow and single narrow treatments for that distance, indicating a significant edge interaction (see Table 2)

abiotic conditions suitable for increased tree growth or increased layering — similar to that observed by Dabros et al. (2017) and MacFarlane (2003) at the edges of wide and narrow seismic lines in upland stands. We believe this surface drying between multiple narrow seismic lines could be contributing to the edge interactions observed in moderate-rich fens. As hypothesized, we found that single seismic lines had a positive edge influence on diversity in moderate-rich fens, but multiple narrow seismic lines did not have an edge influence on diversity. This weakened edge influence on plant diversity for multiple narrow seismic-line edges could be due to surface drying causing a general loss of species with wetter habitat preferences and limiting any increase in edge-associated fen species. We can see evidence of this in the decline in species associated with wetter sites, such as *Salix pedicellaris* and *Larix laricina*, at the edges of the multiple narrow treatment, with no accompanying increase in cover of *Salix planifolia* and *Smilacina trifolia*, as was observed at the edges of the single seismic lines. Future studies should verify this by examining how multiple seismic lines affect peatland hydrology (see Braverman & Quinton, 2016 for the hydrological impacts of seismic lines in a zone of discontinuous permafrost). Our study is focused on one region of narrow seismic lines with relatively low sample sizes. Additional research should build on these results by exploring these effects for other narrow seismic lines in various site types.

In general, Dabros et al. (2017) found edge influence from a single narrow seismic line did not extend past 15 m from the seismic line. We found deeper edge influence: single wide seismic lines had a DEI of up to 50 m in moderate-rich fens, single narrow seismic lines had a DEI of 25 m in moderate-rich fens and between 25 to 50 m in poor fens, and multiple narrow seismic lines had a DEI of at least 25 m from the seismic line in both poor and moderate-rich fens. Interestingly, these distances of edge influence are also larger than that of edges from harvesting — a much larger disturbance (Harper et al., 2016) and may be due to treed peatlands being more sensitive to disturbances compared to upland forests. Since edge influence can change over time (Dupuch & Fortin, 2013; Harper et al., 2016;

Ries et al., 2004), additional research is needed to explore how these distances of edge influence and evidence of edge interaction may change over time, in particular as the vegetation on the seismic line changes.

As previous studies have noted, extrapolating edge influences to landscape scales requires a better understanding of edge interactions (Porensky & Young, 2013; Ries et al., 2017). Our study shows that though smaller (narrower) disturbances may not have an edge influence when they occur singly, the edge interaction from multiple small disturbances results in a much larger edge influence. This highlights the need for more studies on edge interaction. Our results address another piece of the puzzle on the cumulative effects of landscape dissection from oil and gas extraction in the boreal landscape. Although total forest conversion is low in the region (~6% loss), it is the dissection of habitats by linear disturbances that has the largest potential effect on the region's biodiversity when considering their edge effects (Riva & Nielsen, 2021). And although low-impact seismic lines were designed to mitigate the negative environmental impacts of conventional seismic lines, placing them at the high densities as occurs in areas of concentrated oil-sands developments may detract from their benefits.

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AUTHOR CONTRIBUTIONS

All authors conceived of the research idea; Laureen Echiverri collected data; Laureen Echiverri performed statistical analyses with guidance from S. Ellen Macdonald and Scott E. Nielsen; Laureen Echiverri, with edits and contributions from S. Ellen Macdonald and Scott E. Nielsen, wrote the paper; all authors discussed the results and commented on the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.v41ns1rvt.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

Appendix S1 Map of study area

Appendix S2 Diagram of transect and plot layout.

Appendix S3 List of species found in sites.

Appendix S4 Magnitude of edge influence values for response variables in moderate-rich fen sites.

Appendix S5 Average and standard error values for response variables in moderate-rich fen sites.

Appendix S6 Magnitude of edge influence values for cover of dominant understorey species in moderate-rich fen sites.

Appendix S7 Average and standard error values for the cover of dominant understorey species in moderate-rich fen sites.

Appendix S8 Magnitude of edge influence values for response variables in poor fen sites.

Appendix S9 Average and standard error values for response variables in poor fen sites.

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