

Seismic line width and orientation influence microclimatic forest edge gradients and tree regeneration

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ABSTRACT

Ecological impacts of linear anthropogenic disturbances may be underestimated due to edge effects extending into adjacent forests. Seismic lines are the most pervasive linear disturbance associated with oil and gas development in the boreal forests of western North America. The width and orientation of seismic lines may influence microclimatic edge effects that could alter biotic responses, including tree recruitment. We examined light intensity, air temperature, relative humidity, and tree regeneration within seismic lines and adjacent forests to: (1) compare abiotic conditions between wide (6–8 m) and narrow (3–4 m) seismic lines; (2) quantify microclimatic edge effects of seismic lines of different widths and orientations; and (3) relate patterns in tree regeneration density to local patterns in the abiotic environment. We sampled interior forests and 24 seismic lines that were wide or narrow and orientated east-west or north-south in poor mesic ecosites of northeast Alberta, Canada. Microclimatic conditions in seismic line centres were generally intermediate between interior forest and well pads, with narrow seismic lines more similar to interior forest and wide seismic lines more similar to well pads. Light intensity on wide seismic line centres was at least 1.5 times higher than on narrow seismic line centres and up to 3.8 times higher than interior forest. Edge effects on light intensity extended up to 10 m into the forest adjacent to wide lines, but were restricted to the forest edge (at the interface) of narrow lines. Compared to interior forest, day temperature was up to 2.8 °C and 0.8 °C higher at edges of wide and narrow seismic lines, respectively. Relative humidity during the day was up to 7.3% and 3% lower at the edges of wide and narrow seismic lines, respectively, as compared to interior forest. At night, wide seismic line centres were up to 1.7 °C cooler and up to 8.2% more humid than narrow seismic line centres. Tree regeneration was highest where light intensity was highest (the centre of wide north-south seismic lines) and a 10-fold increase in light intensity resulted in 5.8 times more regenerating trees. This study reveals that seismic line width and orientation affect abiotic factors within the linear disturbance and up to 10 m into the adjacent forest. Edge effects on the microclimate of seismic lines were most pronounced in wider seismic lines and along north (south-facing) forest edges. These findings provide a better understanding of the abiotic factors influencing biotic responses to linear anthropogenic disturbances.

1. Introduction

Forest fragmentation due to anthropogenic disturbances alters ecosystems (Saunders et al., 1991) and is consequently a global conservation issue (Riitters et al., 2000; Haddad et al., 2015; Pfeifer et al., 2017). Resource extraction by the oil and gas industry causes widespread forest fragmentation with reductions in forest cover and increases in edge density (Pickell et al., 2015; Rosa et al., 2017). Seismic lines, which are linear forest disturbances created for energy exploration, increase the density of anthropogenic edges (Schneider et al., 2003) and are the

leading cause of forest fragmentation in areas exposed to the oil and gas industry (Pattison et al., 2016). In a 4022 km² area of western Canada's boreal forest, Pattison et al. (2016) reported that seismic lines accounted for 80% of edges, and the density of seismic lines was more than twice that of all other anthropogenic linear features combined.

There are generally two types of seismic lines: (1) conventional seismic lines that are 5–10 m wide and separated by distances of 300–500 m; and (2) narrow, or low-impact, seismic lines that are typically 1.5–4 m wide and spaced at distances of 50–100 m apart (EMR, 2006). Although narrower seismic lines are more commonly used today

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to mitigate some of the negative environmental impacts of these linear disturbances (CAPP, 2004; EMR, 2006; Dabros et al., 2018), delayed forest regeneration on seismic lines is an ecological concern regardless of line width (Kansas et al., 2015).

Effects of seismic line disturbances include altered habitat use by birds (Bayne et al., 2005; Machtans, 2006; Ashenhurst and Hannon, 2008; Lankau et al., 2013), butterflies (Riva et al., 2018a), and mammals (Dyer et al., 2001; Tigner et al., 2014; Tigner et al., 2015; Fisher and Burton, 2018; Dickie et al., 2020). Seismic lines are used as travel corridors by predators such as wolves (Latham et al., 2011; McKenzie et al., 2012; Dickie et al., 2017) thereby influencing predation rates of woodland caribou (James and Stuart-Smith, 2000; Mumma et al., 2017; DeMars and Boutin, 2018), which is a species of conservation concern (COSEWIC, 2002). Seismic lines also have the potential to increase seed dispersal (Roberts et al., 2018) and alter plant communities (Finnegan et al., 2018; Riva et al., 2020). Recovery rates of woody vegetation on seismic lines are slow (Lee and Boutin, 2006) and the lack of regeneration on seismic lines could persist up to 50 years post-disturbance (van Rensen et al., 2015).

A better understanding of the microclimatic variables affecting tree growth and establishment on seismic lines could help guide restoration efforts for caribou habitat. Compared to intact forest, seismic lines are characterized by higher wind speeds and light intensity (Stern et al., 2018), as well as higher soil temperature and moisture (Revel et al., 1984; Dabros et al., 2017). In general, areas with open canopy are also characterized by higher air temperature and lower relative humidity than intact forests (Ghuman and Lal, 1986), yet these abiotic variables have been predominately investigated in large forest clearings (e.g., clearcuts) with their responses to smaller forest gaps associated with narrow seismic lines (<10 m widths) largely unknown.

The cumulative effects of seismic lines on a landscape-scale may be underestimated due to edge effects that extend beyond the cleared lines (Dabros et al., 2018). Edge influence can be quantified as either the *magnitude* of edge influence, which is the extent to which a given response variable differs at the forest edge as compared with the interior forest (intact forest unaffected by edge), and as the *distance* of edge influence, which is the distance from the edge into the adjacent forest over which a given response variable is significantly different from the interior forest (Harper et al., 2005). Edge influence on understory vegetation extended up to 15 m from narrow (~2–3 m) seismic lines (Dabros et al., 2017). Furthermore, tree height and vegetation cover were reduced within 5–15 m of seismic line centres (Abib et al., 2019). Although studies on biotic edge gradients are informative, research on abiotic mechanisms is needed to provide insight into potential explanations for biotic edge-associated patterns (Murcia, 1995). Changes in the abiotic environment are considered direct effects of edge creation that ultimately contribute to indirect effects of edges, including vegetation growth and regeneration (Harper et al., 2005).

Edge effects may depend on seismic line characteristics, such as orientation and width (Revel et al., 1984). In the northern hemisphere, south-facing edges have greater light levels and are typically warmer and drier than north-facing edges (Wales, 1967; Matlack, 1993). While microclimatic variables were strongly influenced by edge orientation at forest edges adjacent to clearcuts (Chen et al., 1993; Chen et al., 1995) and fields (Matlack, 1993; Young and Mitchell, 1994), other studies revealed no significant influence of orientation on microclimate (e.g., Dovciak and Brown, 2014). Although Dabros et al. (2017) detected edge influence on solar radiation 5 m from narrow (~2–3 m) seismic line edges, the edge effect on light could be greater for wider seismic lines and influencing other abiotic variables such as air temperature and relative humidity. Little is known about the relationship of these abiotic factors to tree regeneration on seismic lines, which is of interest for ecological restoration (Pyper et al., 2014; Dabros et al., 2018).

This study investigated the influence of seismic line width, orientation, and edges on tree regeneration density and microclimate, which included light intensity, air temperature, and relative humidity. Our

research objectives were to: 1) compare microclimate and tree regeneration between the centres of wide and narrow seismic lines; 2) determine the effects of seismic line width and orientation on the magnitude and distance of edge influence on microclimate and tree regeneration; and 3) investigate the relationship between the microclimate and tree regeneration density on seismic lines and in adjacent poor mesic forests. We predicted that differences in microclimate between seismic lines and interior forest (25 m from the forest edge) would increase with width of disturbance and would be greatest at south-facing edges. We used the interior forest and nearby larger openings associated with exploratory well drilling (well pads) to represent reference closed-canopy forest and open clearings, respectively. These findings will quantify the effects of seismic lines on microclimate and tree regeneration and ultimately help improve guidelines for forest restoration of these common and persistent disturbances in Canada's western boreal forests.

2. Methods

2.1. Data collection

The study area was situated in the boreal forest of northeast Alberta, Canada (Fig. 1). Daily average temperature was 17.1 °C and −17.4 °C in July and January, respectively, and mean annual rainfall was 316.3 mm in nearby Fort McMurray (56°39'00"N, 111°13'00"W) from 1981 to 2010 (Government of Canada, 2019). We conducted research exclusively in poor mesic ecosites dominated by black spruce (*Picea mariana*) in the overstory and Labrador tea (*Rhododendron groenlandicum*), bog cranberry (*Vaccinium oxycoccos*), and feather mosses in the understory (Beckingham and Archibald, 1996).

There were six site replicates of each of four seismic line width and orientation combinations (wide lines oriented east–west, wide lines oriented north–south, narrow lines oriented east–west, and narrow lines oriented north–south) for a total of 24 sampled seismic lines. Wide lines were conventional seismic lines that ranged in width from 6 m to 8 m, while narrow lines were low impact seismic lines that ranged in width from 3 m to 3.9 m (Fig. 2). Sites were located > 25 m from seismic line intersections, >60 m from other forest edges, and > 100 m from roads. Sites were never located on the same seismic line, except for five sites that were located on two different seismic lines and separated by a minimum distance of 400 m. According to Nash (2011a) and satellite imagery in Google Earth Pro, the majority of seismic lines were cleared 10–13 years prior to sampling; however, the exact establishment dates are not known for some seismic lines, which could have been cleared up to 28 years prior to sampling (Appendix 1). Average ± standard error of tree height, which we measured with a hypsometer (Vertex IV Haglöf, Sweden) at each site, was 9.9 ± 0.7 m and 9.4 ± 0.4 m adjacent to wide lines and narrow lines, respectively. Seismic lines were devoid of any restoration treatment and had minimal natural shrub/tree regeneration (maximum height < 1.3 m and stem density < 30 stems/10 m²; measured in 10 m² sampling plots located in seismic line centres).

Three nearby exploratory well pad sites (largest openings in the area) were used to represent open canopy conditions. The inclusion of well pads enabled us to determine if abiotic conditions on seismic lines were similar to those in non-linear forest clearings with no canopy cover. The well pads were devoid of infrastructure, square in shape, and ranged in size from 0.48 ha to 0.55 ha.

At each site, we established a transect perpendicular to the seismic line-forest edge and centred in the middle of the seismic line extending in both cardinal directions (east [E] and west [W] for north–south oriented lines; north [N] and south [S] for east–west oriented lines). Microclimate stations were located in the middle of the seismic line (centre) and at the following distances from the edges into the interior forest: 0 m (at the forest edge), 5 m, 10 m, and 25 m into the forest (Appendix 2). We defined the seismic line-forest edge as the limit of continuous stems at the interface between the seismic line and adjacent

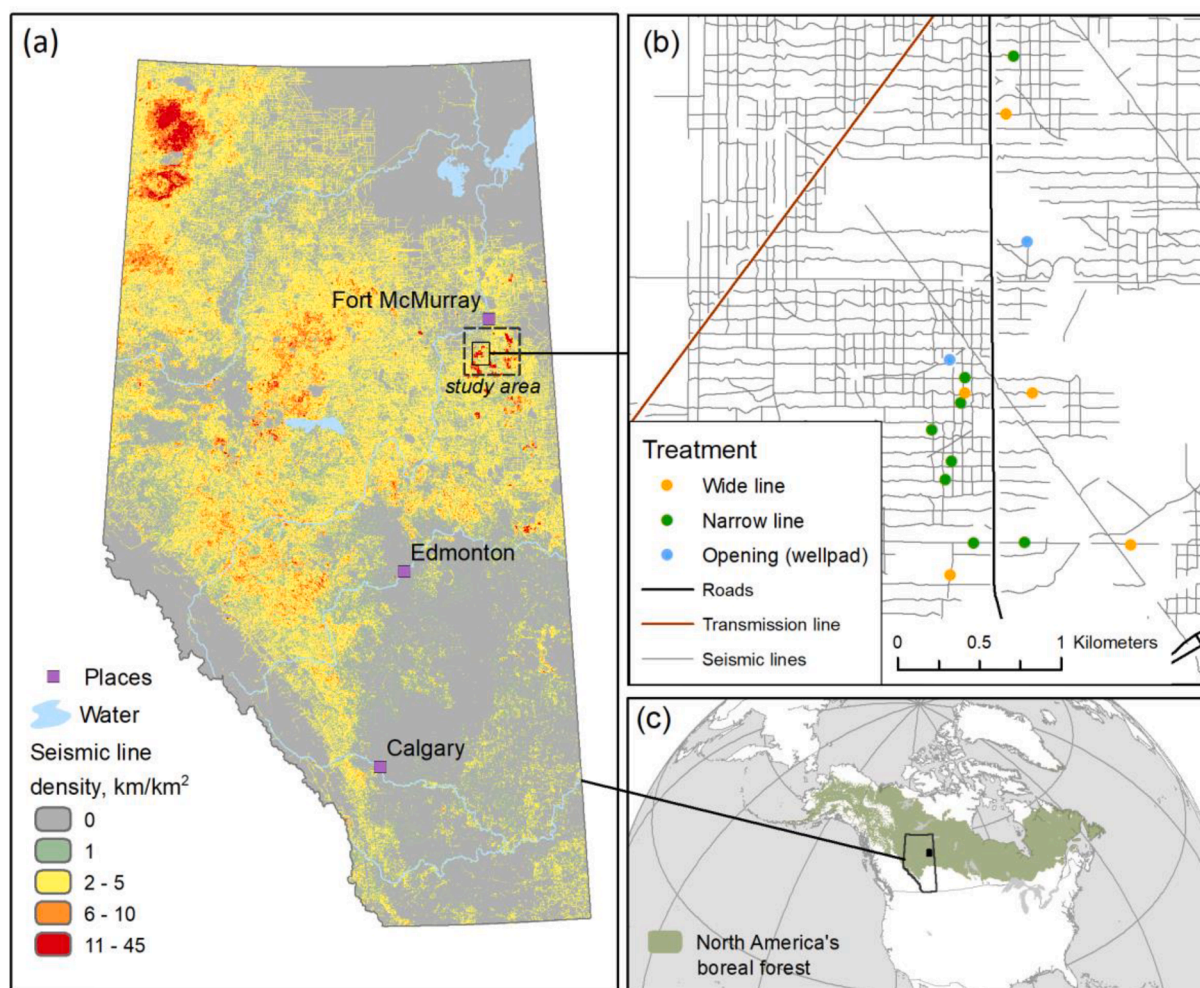


Fig. 1. Seismic line density and study area location in the province of Alberta, Canada used to assess the effects of seismic lines on microclimate and tree regeneration (a), locations of a selection of study sites from one sub-study area (b), and the provincial boundary of Alberta relative to the distribution of North America's boreal forest biome (c). Seismic line density is based on the Alberta Biodiversity Monitoring Institute Wall-to-Wall Human Footprint Inventory 2018.

forest. At well pad sites, microclimate stations were situated in the middle of the well pad to represent a deforested area with no canopy cover.

We collected data at seismic line and well pad sites from 7 June to 7 August 2018. Although microclimate data collection time varied by site (Appendix 1), we sampled each site for at least nine consecutive days, with the exception of one site that we sampled for five days. We were unable to sample all sites simultaneously due to a limited number of sensors, but we ensured that we sampled well pad sites and seismic lines representing different orientations and widths concurrently throughout the sampling period to account for daily weather variations. Orientation of lines sampled was systematic to ensure no directional bias of results due to changes in the sun angle over the period of the study.

Each microclimate station recorded light intensity, air temperature, and relative humidity. HOBO pendant data loggers (Onset Computer Corporation, Bourne, Massachusetts, USA) recorded light intensity in lux every five minutes at a height of 1.2 m above ground. Hygrochron iButtons (DS1923; Maxim Integrated, San Jose, California, USA) recorded temperature and relative humidity every 15 min at a height of 15 cm above ground layer vegetation to represent growing conditions of tree regeneration in the understory. iButtons were shielded using small radiation shields as described in Terando et al. (2017) and modified from Holden et al. (2013). We recorded the number and species of regenerating tree saplings (<1.3 m in height) within a 1.78 m radius plot (10 m²) centred at each microclimate station and reported the density of

regenerating trees in stems per hectare.

2.2. Data analysis

We excluded abiotic sensor deployment and retrieval dates from sampling time periods for analyses. There were 3096 (light) or 2844 (temperature and relative humidity) observations, each representing a location relative to a seismic line on a specific sampling day. We calculated average (mean) daily light intensity by averaging the measurements recorded every five minutes between the times of sunrise and sunset for each sampling day, which we retrieved for each site from National Research Council Canada (2018). Temperature and relative humidity measurements at 1200 h and 2400 h represented day and night, respectively. We analyzed all data in the R statistics programming environment version 3.5.2 (R Core Team, 2018).

2.2.1. Edge influence on microclimate and tree regeneration

We defined 'edge effect/influence' as the distance from the seismic line-forest edge at which the response variable was significantly different from the interior forest (Harper et al., 2005). We consider the 'interior forest' as the furthest distance from the edge into the adjacent forest that was sampled, which was 25 m. It would have been challenging to sample further from the edge into the forest because of the high density of seismic lines (sometimes spaced 50 m apart). Nevertheless, edge effects in boreal forest are generally weak extending <20 m

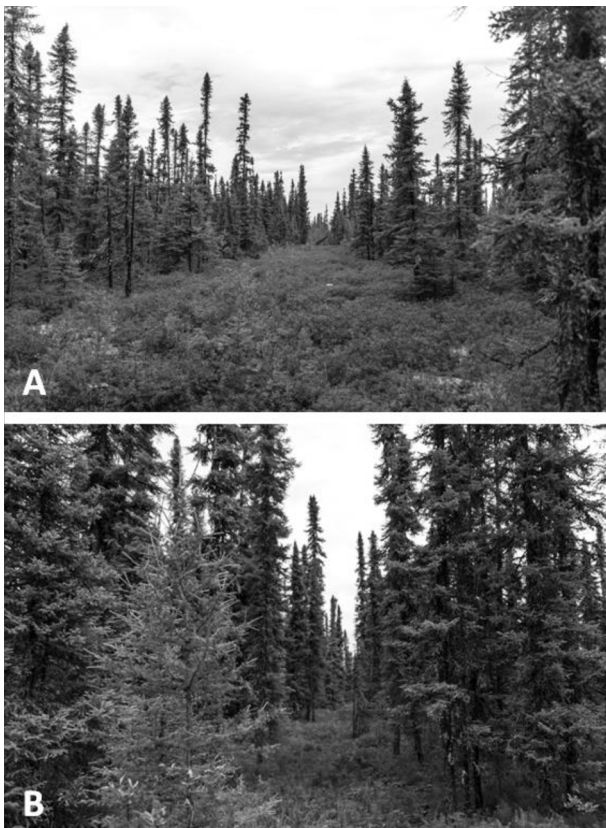


Fig. 2. Representative examples of wide (A) and narrow (B) seismic lines in northeast Alberta, Canada that were sampled to examine the influence of seismic line width and orientation on abiotic factors and tree regeneration. Photos by S.E.N.

into the forest (Gignac and Dale, 2005; Harper et al., 2015; Dabros et al., 2017).

For the linear mixed effects models described below, fixed independent predictor variables were: 1) location of the microclimate stations on the transect relative to the edge at 0 m (hereafter referred to as 'location on transect'); 2) seismic line width (hereafter referred to as 'line width'); and 3) the interaction between location on transect and line width. Location on transect was a categorical variable with the following 18 levels: E-W seismic line centre, N-S seismic line centre, and each distance from the edge into adjacent forest (0 m, 5 m, 10 m, 25 m) for each cardinal direction (N, S, E, W). Line width was a categorical variable with wide and narrow as two different levels.

To examine the effects of seismic lines on microclimate (continuous variables), we created linear mixed effects models with Gaussian distribution using the lmer function in the lme4 package (Bates et al., 2019). We developed five separate models, one for each of the following response variables: average daily light intensity, day temperature, night temperature, day relative humidity, and night relative humidity. Site and day were crossed random effects. We assessed and confirmed assumptions of normality and homoscedasticity of the residuals using diagnostic plots (Meuleman et al., 2014). We excluded data from the well pads (reference openings) in the models because well pads had nothing comparable to the width and orientation categories. We therefore obtained means and standard error values for the well pads by creating separate models that excluded seismic line width. We do not present these results because we were only interested in the means and standard errors representing the well pads for comparative purposes.

To determine the impact of seismic lines on tree regeneration density (count data), we created a generalized linear mixed effects model with Poisson distribution (link = log) using the glmer function in the lme4

package (Bates et al., 2019). We removed one outlier with an unusually high number of saplings (possible recording error) for analysis. Tree regeneration density was the response variable and site was a random effect.

Pairwise comparisons were made using the emmeans package (Lenth et al., 2019) and *P* values were adjusted using Holm's sequential Bonferroni correction to account for multiple comparisons. We compared the response variables between the centres of seismic lines with different widths (wide, narrow) and orientations (east–west, north–south) to investigate the influence of width and orientation on response variables in the centres of seismic lines (objective 1). To investigate edge influence (objective 2), we compared response variables at 0 m, 5 m, and 10 m for each width and cardinal direction to those at the 25 m location on the same side of the seismic line (e.g., 5 m from the north edge of the wide line was compared to 25 m from the north edge of the wide line; 5 m from the west edge of the narrow line was compared to 25 m from the west edge of the narrow line). The seismic line centres were compared to either the south side (east–west seismic lines) or west side (north–south seismic lines).

2.2.2. Relationships between microclimate and tree regeneration

To examine the relationship between regeneration density and microclimate (objective 3), we created generalized mixed effects models with negative binomial distribution (link = log) using the glmer.nb function in the lme4 package (Bates et al., 2019). We developed a separate model for each of the following predictor variables (log10 transformed): average daily light intensity (sunrise to sunset), average daily temperature (over a 24-hour period), and average daily relative humidity (over a 24-hour period). We averaged the predictor variables over the sampling period for each microclimate station. Regeneration density was the response variable and site was a random effect. We tested nonlinear effects by adding the quadratic term of the abiotic predictor variable to the models, which we compared to the linear models using the Akaike information criterion (AIC) value. For each of the abiotic variables, the linear model was more supported (lower AIC) hence it is the only model presented.

3. Results

The interaction between location on transect and seismic line width was significant for each of the abiotic response variables (Table 1).

3.1. Light intensity

Light intensity on wide seismic line centres was higher than on narrow seismic line centres by 1.5 times and 2.0 times for east–west and north–south orientations, respectively (Fig. 3). On east–west seismic lines, light intensity was higher in the centres and at the edges of both narrow and wide seismic lines compared to the interior forest (Fig. 3A). Light intensity was lower than in the interior forest 10 m from the north edge of wide seismic lines, where canopy cover was highest (Fig. 3A; Appendix 3). Light intensity on north edges of wide and narrow seismic lines was 2.8 times and 1.7 times, respectively, higher than light intensity on south edges (Fig. 3A). On wide north–south seismic lines, light intensity was highest in the seismic line centre and was 2 times higher on the east edge as compared to the west edge (Fig. 3B). In contrast, differences in light intensity between edges of narrow north–south seismic lines were attenuated (Fig. 3B). Edge effects on light intensity for north–south seismic lines extended 5 m into the forest adjacent to wide seismic lines, but were restricted to the forest edge on narrow seismic lines (Fig. 3B). Light intensity on well pads was up to 2.5 times higher than on seismic lines (Fig. 3).

3.2. Air temperature

When compared to day temperature in the interior forest, day

Table 1

Results of mixed models (F values, degrees of freedom [df], and P values) examining the influence of location on transect, line width, and location on transect \times line width interaction on abiotic and biotic response variables investigated in Alberta, Canada. Location on transect includes east–west seismic line centre, north–south seismic line centre, and distance from seismic line edge into adjacent forest (0 m, 5 m, 10 m, 25 m) for each cardinal direction. Line width includes wide (6–8 m) and narrow (3–4 m) categories. Bold indicates significance ($P < 0.05$). P values are omitted for regeneration (count data) because model used Poisson distribution.

Response variable	Location on transect			Line width			Location on transect \times Line width		
	F	df	P	F	df	P	F	df	P
<i>Light</i>									
Daily average	207.78	17	<0.001	9.12	1	0.006	39.29	17	<0.001
<i>Temperature</i>									
Day	51.74	17	<0.001	0.002	1	0.963	8.59	17	<0.001
Night	18.64	17	<0.001	1.20	1	0.285	5.79	17	<0.001
<i>Relative humidity</i>									
Day	27.46	17	<0.001	0.10	1	0.754	7.28	17	<0.001
Night	10.66	17	<0.001	7.19	1	0.018	6.06	17	<0.001
<i>Regeneration</i>	8.77	17	–	4.14	1	–	4.80	17	–

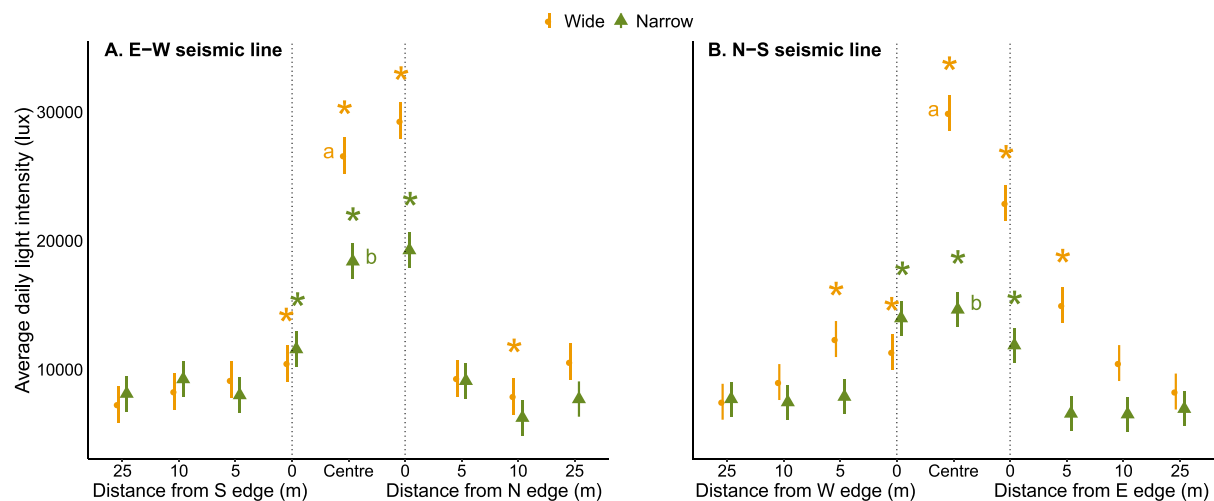


Fig. 3. Results of mixed model examining average daily light intensity (estimated marginal means \pm standard error) on seismic line centres and at four distances from wide (6–8 m) and narrow (3–4 m) seismic line-forest south (S), north (N), west (W), and east (E) edges in Alberta, Canada. Lowercase letters correspond to comparisons between means for the seismic line centres. Means sharing a letter are not significantly different (pairwise comparison of estimated marginal means, $P \geq 0.05$ Bonferroni adjusted). Asterisks indicate means that are significantly different ($P < 0.05$) than interior forest (25 m from edge). Mean \pm standard error of well pads was $59\,260 \pm 2176$ lx.

temperature in the seismic line centres was 1.6°C higher on wide east–west seismic lines and 0.9°C higher on wide north–south seismic lines (Fig. 4A–B). Day temperature was 2.8°C higher at wide north edges, 0.8°C higher at narrow north edges, and 0.6°C higher at wide south edges, but was not significantly different at narrow south edges as compared to the interior forest (Fig. 4A). Wide seismic lines also experienced greater edge effects than narrow seismic lines oriented north–south, as day temperature was 2.3°C higher at wide west edges and 0.8°C higher at narrow west edges as compared to the interior forest (Fig. 4B). Edge effects on day temperature for north–south seismic lines extended 5 m into the forest on the east side of wide seismic lines, but did not extend beyond the forest edge on the west side of wide seismic lines and both sides of narrow seismic lines (Fig. 4B). Although seismic lines had higher day temperatures than undisturbed forest, they were not as warm as well pads, which were $> 1.5^\circ\text{C}$ warmer than seismic line centres and edges (Fig. 4A–B).

In comparison to the forest interior, night temperature was 1.3°C lower at the centre of wide east–west seismic lines, 0.5°C lower at the centre of narrow east–west seismic lines, 0.6°C lower at the centre of wide north–south seismic lines, and not significantly different at the centre of narrow north–south seismic lines (Fig. 4C–D). On east–west seismic lines, edge influence on night temperature extended to 10 m on the north side of wide seismic lines, was restricted to the north edge of narrow seismic lines, and was absent on the south sides for both seismic

line widths (Fig. 4C). On the north–south seismic lines, edge influence on night temperature extended to 10 m on the east side of wide seismic lines, extended to 5 m on the east edge of narrow seismic lines, and was absent on the west side for both seismic line widths (Fig. 4D). Night temperature was $\geq 1.5^\circ\text{C}$ and $\geq 2.5^\circ\text{C}$ warmer on centres of wide and narrow seismic lines, respectively, than in well pads (Fig. 4C–D).

3.3. Relative humidity

Relative humidity during the day did not differ between the seismic line centres, but was 3.8% lower in the centre of wide north–south seismic lines than in the interior forest (Fig. 5A–B). Compared to the interior forest, relative humidity during the day was 7.3% lower at the north edge of wide seismic lines and 3% lower at the north edge of narrow seismic lines (Fig. 5A). Edge influence on day relative humidity extended to 5 m from the edge into the forest adjacent to wide seismic lines (north and east edges) and to 10 m from the edge into the forest adjacent to narrow seismic lines (east and west edges) (Fig. 5A–B). Relative humidity during the day was lowest at the west edge of wide seismic lines, where it was 7% lower than the interior forest and only 3.8% higher than well pads (Fig. 5B).

Relative humidity at night was higher overall on wide seismic lines, illustrating that wide seismic lines experienced greater daily fluctuations in atmospheric moisture than narrow seismic lines (Fig. 5C–D). Relative

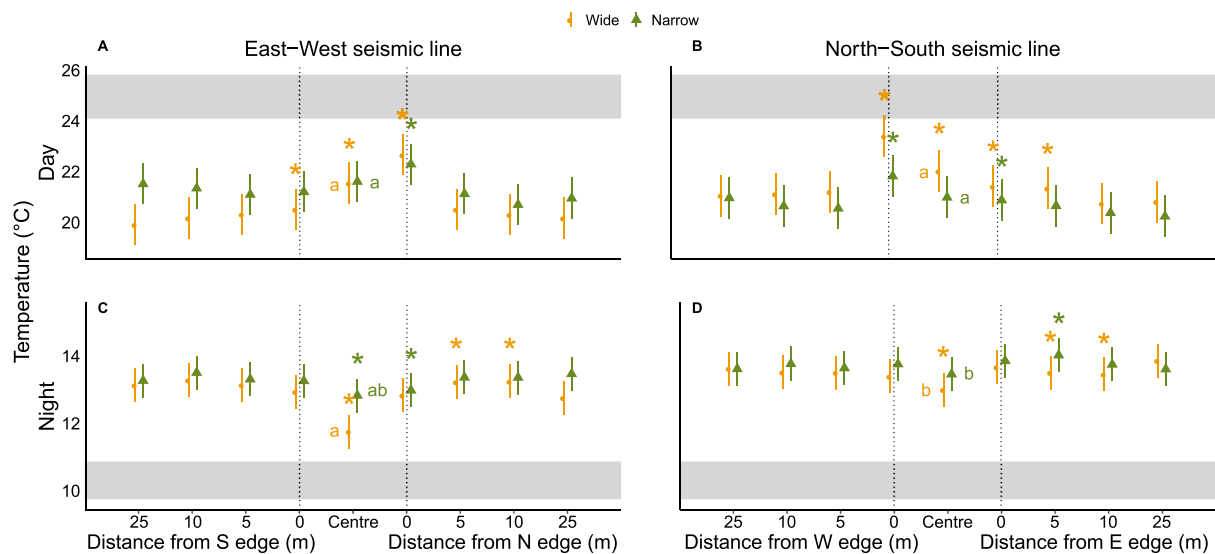


Fig. 4. Results of mixed models examining air temperature (estimated marginal means \pm standard error) during the day (A-B) and night (C-D) on seismic line centres and at four distances into the forest for wide (6–8 m) and narrow (3–4 m) seismic lines along south (S), north (N), west (W), and east (E) forest edges in Alberta, Canada. Lowercase letters correspond to comparisons between means for the seismic line centres. Means sharing a letter are not significantly different (pairwise comparison of estimated marginal means, $P \geq 0.05$ Bonferroni adjusted). Asterisks indicate means that are significantly different ($P < 0.05$) than interior forest (25 m from edge). Gray shaded area represents the mean \pm standard error of large open forest conditions (~0.5 ha well pads).

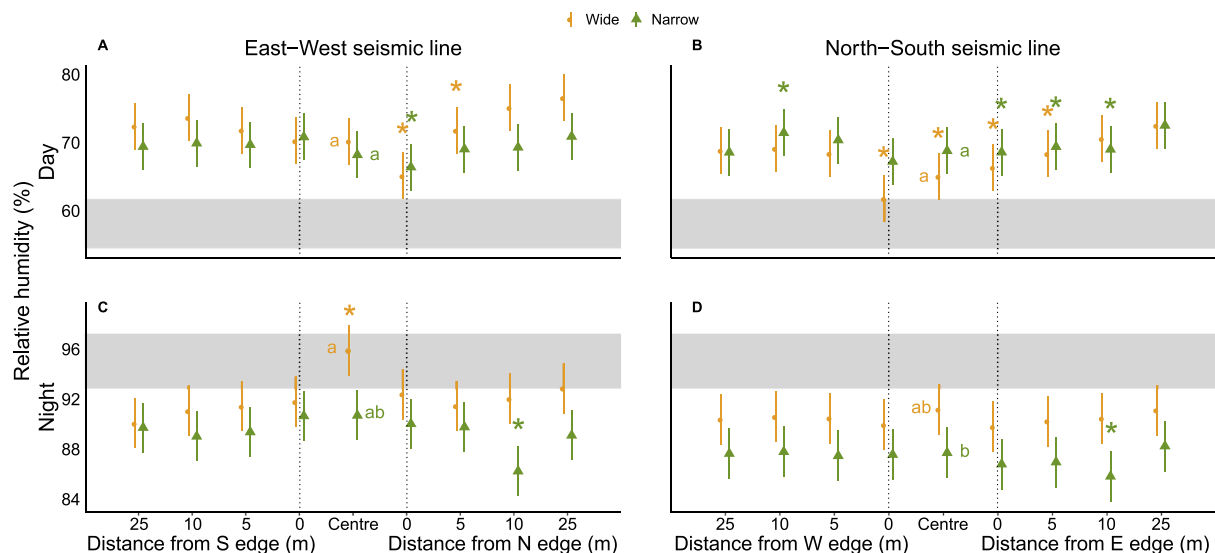


Fig. 5. Results of mixed models examining relative humidity (estimated marginal means \pm standard error) during the day (A-B) and night (C-D) on seismic line centres and at four distances into the forest for wide (6–8 m) and narrow (3–4 m) seismic lines along south (S), north (N), west (W), and east (E) forest edges in Alberta, Canada. Lowercase letters correspond to comparisons between means for the seismic line centres. Means sharing a letter are not significantly different (pairwise comparison of estimated marginal means, $P \geq 0.05$ Bonferroni adjusted). Asterisks indicate means that are significantly different ($P < 0.05$) than interior forest (25 m from edge). Gray shaded area represents the mean \pm standard error of large open forest conditions (~0.5 ha well pads).

humidity at night was highest in the centre of the wide east–west seismic line, where it was $\geq 3\%$ higher than interior forest and most similar to well pads (Fig. 5C). Relative humidity at night was not significantly different than the interior forest at any locations along the narrow seismic lines, except for at 10 m from north and east edges (Fig. 5C-D).

3.4. Responses in tree regeneration to seismic lines and abiotic factors

Black spruce (*Picea mariana*) accounted for an average of 97% of regenerating stems in sampling plots while the remaining stems were tamarack (*Larix laricina*). Tree regeneration density was affected by the interaction between seismic line orientation and width (Table 1; Fig. 6).

Regeneration density was higher in the centres of wide seismic lines than in the centres of narrow seismic lines regardless of line orientation (Fig. 6). Compared to interior forest, regeneration density was higher in the centre of wide seismic lines oriented in both directions and lower in the centre of narrow east–west seismic lines (Fig. 6). Edge influence on regeneration density only occurred at 10 m from the south edge of narrow seismic lines (Fig. 6).

A 10-fold increase in light intensity resulted in 5.8 times more regenerating tree stems/ha (Table 2; Fig. 7). Although regeneration density was also positively related to temperature and humidity, the relationships were not significant (Table 2), suggesting that changes in orientation and width of seismic lines that altered light patterns were

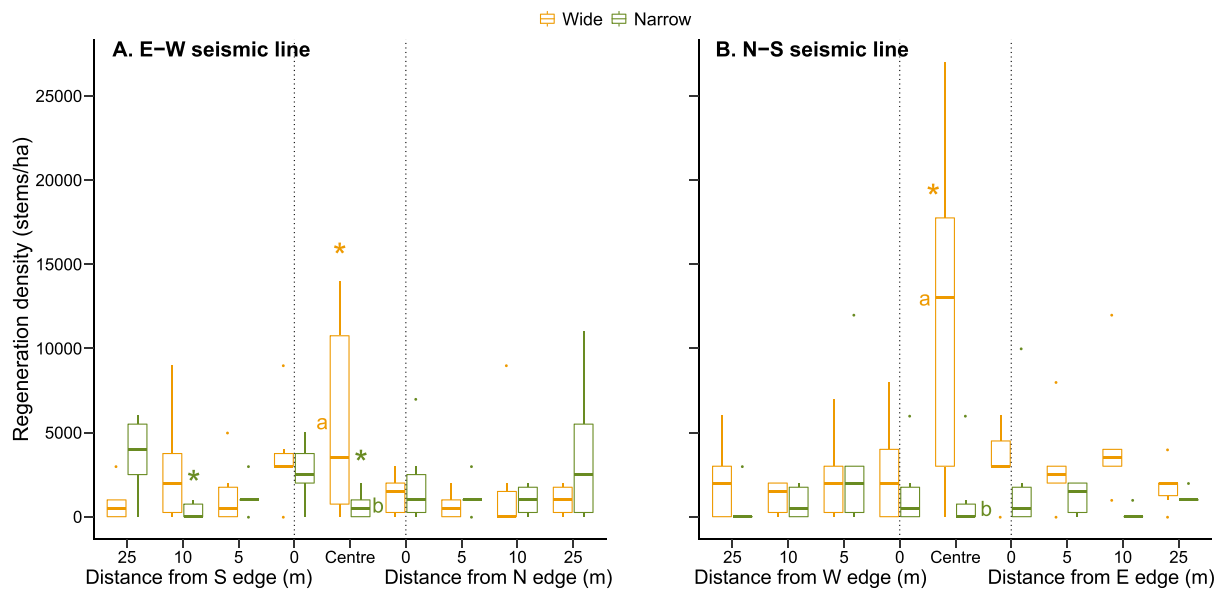


Fig. 6. Results for mixed models examining tree regeneration density (box-plots with median, 25th, and 75th percentiles) on seismic line centres and at four distances from wide (6–8 m) and narrow (3–4 m) seismic line-forest south (S), north (N), west (W), and east (E) edges in Alberta, Canada. Lowercase letters correspond to comparisons between means for the seismic line centres. Means sharing a letter are not significantly different (pairwise comparison of estimated marginal means, $P \geq 0.05$ Bonferroni adjusted). Asterisks indicate means that are significantly different ($P < 0.05$) than interior forest (25 m from edge).

Table 2

Results of negative binomial regression models (beta coefficients [β] with standard error [SE], F values, and P values) examining the influence of light intensity (log10 transformed), temperature (log10 transformed), and relative humidity (log10 transformed) on regeneration density investigated on and adjacent to wide (6–8 m) and narrow (3–4 m) seismic lines in Alberta, Canada. Bold indicates significance ($P < 0.05$).

Predictor variable	β (SE)	F	P
Average daily light intensity	1.75 (0.39)	21.27	<0.001
Average daily temperature	0.08 (4.23)	<0.001	0.984
Average daily relative humidity	1.92 (3.49)	0.33	0.582

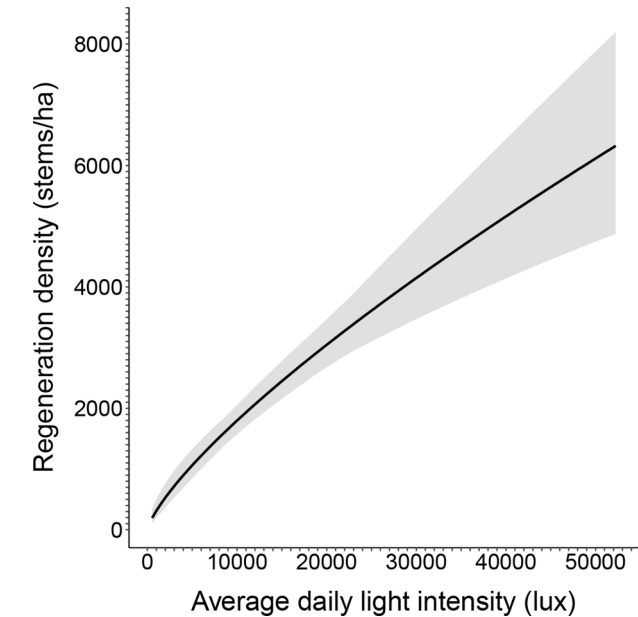


Fig. 7. Relationship between average daily light intensity and tree regeneration density (stems/ha) on and adjacent to seismic lines in Alberta, Canada as predicted by a negative binomial regression model.

most responsible for local observed patterns in tree regeneration.

4. Discussion

Our findings reveal that abiotic responses to forest gaps associated with seismic lines varied by line width and orientation. Microclimatic conditions in the middle of seismic lines were generally intermediate between interior forest and well pads, with narrow seismic lines more similar to interior forest and wide seismic lines more similar to well pads. Seismic lines in our study area not only altered the abiotic environment on the linear disturbance itself, but the abiotic effects of the disturbance extended up to 10 m into the adjacent forest. Compared to narrow seismic lines, wide seismic lines had greater edge influence. In addition to seismic line width, orientation also influenced microclimate as edge effects were generally more pronounced at south-facing and west-facing seismic line edges.

Greater canopy openness in wider seismic lines enabled increased light penetration that extended into the forest. Centres of wide seismic lines were characterized by >1.5 times light intensity than those of narrow seismic lines. These results corroborate other studies that revealed positive relationships between light intensity and seismic line width (Williams and Quinton, 2013; Stern et al., 2018). In our study, light intensity up to 5 m from the seismic line-forest edge into the interior forest was greater than light intensity in the interior forest, which is a finding that could be attributed to forest structure. Abib et al. (2019) revealed that canopy height and cover were reduced within 5 m of seismic line centres and the greatest impact was adjacent to wide (>6 m in width) seismic lines. Similar to our findings on wide seismic lines, higher light intensity at east as opposed to west forest edges has been documented for forest canopy gaps (Parhizkar et al., 2011; Ritter et al., 2005). The high light intensity we observed extending further into the interior forest on seismic lines oriented north–south as opposed to east–west could be attributed to edge exposure on east and west sides reflecting the daily sun path from east to west.

Light intensity across seismic lines could be influencing the patterns of temperature and humidity we observed as increased solar radiation results in warmer and drier conditions near the ground (Geiger et al., 2009). High light intensity on seismic lines corresponded to higher temperature and lower humidity on seismic lines than in adjacent forest

during the day. At noon, when the sun was continuing to move from east to west, temperature and humidity reached their highest and lowest levels, respectively, at east-facing and south-facing edges. Chen et al. (1993) also detected more extreme daytime air temperature and relative humidity at forest edges than in the adjacent disturbed area, a finding that was attributed to weaker winds producing more stable air at the edges as opposed to stronger winds that blend air and diminish humidity and temperature variation in the open clearcut area. While seismic lines have higher wind speeds than interior forest (Roberts et al., 2018; Stern et al., 2018), wind speed has yet to be evaluated across seismic line-forest edges, but could be contributing to unique microclimates at the edge of seismic lines.

Our results suggest that daily variations in air temperature and relative humidity increase with size of disturbed area as wide seismic lines had greater daily fluctuations in temperature and humidity than narrow seismic lines and interior forest, while the greatest daily fluctuations in temperature and humidity we observed were on well pads. Large-scale anthropogenic disturbances, such as clearcuts, also have greater daily air temperature differences than forests (Chen et al., 1993). Our findings revealed that north, east, and west seismic line-forest edges, particularly on wide seismic lines, experienced greater daily fluctuations than the interior forest. Greater daily air temperature ranges at the edge than in the interior forest have also been detected for other linear features, such as powerlines, highways, and streams (Pohlman et al., 2009). Extreme temperatures may affect ecological processes, such as black spruce colonization, which is reduced by low nocturnal temperatures in frost hollows during the spring growing season (Dy and Payette, 2007). Future research should consider sampling different seasons to detect potential seasonal differences in microclimatic gradients (Hennenberg et al., 2008).

The differences in edge influence between wide and narrow seismic lines we observed depended on edge orientation. On wide seismic lines, light intensity on north edges was 2.8 times greater than south edges and light intensity on east edges was 2 times greater than light intensity on west edges. Meanwhile, differences in light intensity between edges of narrow seismic lines were attenuated, but the highest light intensity also occurred at the north edge. During the day, south-facing edges had greater temperatures and lower humidity levels than north-facing edges and interior forest for both wide and narrow seismic lines; however, the magnitude of edge influence was greater for wide seismic lines. Differences in light intensity, temperature, and humidity between the south edges of wide and narrow seismic lines were negligible. Dabros et al. (2017) revealed that orientation did not significantly affect edge influence on the microclimate adjacent to seismic lines that were narrower (~2–3 m in width) than the ones we investigated. Consequently, effect of orientation on edge influence may strengthen with greater widths of linear disturbances. High light intensity at south-facing edges could be enhancing tree growth, which Revel et al. (1984) reported to be highest at south-facing seismic line edges compared to other cardinal directions. Meanwhile, high light intensity may reduce growth and survival of feather mosses, which are limited by evaporation stress and radiation damage (Busby et al., 1978). Previous studies reported reduced bryophyte growth (Hylander, 2005) and lichen species diversity (Kivistö and Kuusinen, 2000) at south- rather than north-facing edges. Our results indicate that species with microclimate sensitivities may be more negatively affected at edges of wider seismic lines, which had more pronounced microclimatic edge effects than narrow seismic lines.

The relatively low extent of edge influence on the microclimatic environment for seismic lines is not surprising because seismic lines are relatively narrow and edge influence in the boreal forest is often low compared to temperate and tropical forests (Harper et al., 2005). Our study revealed that maximum distance of edge influence for seismic lines was 10 m from the edge into the forest. In boreal forest adjacent to farmland, there were significant decreases in light intensity and daytime temperature accompanied by increases in daytime humidity up to 15 m from the edge into the forest (Gignac and Dale, 2005). As compared to

larger polygonal disturbances, relatively narrow linear features, such as seismic lines, could result in lower edge influence. Even in subtropical forest, where edge effects are common, significant changes in light and temperature, as compared to intact forest, dissipated within 6 m from narrow roads (6–7 m wide) (Delgado et al., 2007).

Our findings demonstrate that regeneration density on seismic lines increased by 5.8 times for each 10-fold increase in light intensity. Higher light intensity on wide seismic lines when compared to narrow seismic lines could have contributed to more regeneration on wide lines than narrow lines. The majority of regenerating saplings we encountered were black spruce, which was the dominant overstory species in the adjacent forests and grows well in open canopy conditions (Fowells, 1965). Higher light intensity on seismic lines than in interior forest may also contribute to the increased regeneration density of jack pine (*Pinus banksiana*) on seismic lines adjacent to xeric forests (Filicetti and Nielsen, 2018). In addition to tree saplings, increased light intensity could explain the abundance of other shade intolerant understorey plants found on seismic lines in previous studies (MacFarlane, 2003; Finnegan et al., 2018). Similar to our findings, Dabros et al. (2017) did not detect edge influence on woody plants; however, herbaceous plant species diversity was lower at seismic line-forest edges up to 15 m into adjacent forest and diversity and cover of non-vascular plant species was lower at seismic line-forest edges compared to interior forest. Therefore, microclimatic gradients at seismic line-forest edges may be affecting ecological patterns and processes we did not investigate, such as tree growth, which has been reported to be higher at seismic line edges than in the interior forest (Revel et al., 1984; Bella, 1986).

Whereas wide seismic lines in our study area appeared to be regenerating naturally < 30 years after establishment, regeneration density was lower on narrow seismic lines compared to interior forest. Reduced light intensity could be contributing to decreased regeneration density on narrow seismic lines, in which case active restoration efforts may be beneficial for the establishment of saplings on narrow seismic lines, especially on narrow east–west seismic lines where regeneration density was lowest. Nevertheless, narrow seismic lines could have relatively lower regeneration density than wide seismic lines because some of the wide seismic lines were older than the narrow seismic lines and therefore had more time for tree establishment and growth. Our findings should be interpreted with caution because of variability in seismic line year of establishment and a sample size limited to 24 seismic lines.

The effects of seismic lines on microclimate and regeneration could vary by ecosite, especially because van Rensen et al. (2015) revealed that seismic lines in bogs and fens were less likely to regenerate than those in drier forests. For seismic lines adjacent to treed peatlands with lower canopy cover and shorter trees than the poor mesic forests investigated in our study, microclimatic differences between seismic lines and interior forest may be attenuated and edge influence on microclimate may be reduced. Furthermore, light intensity may not be a limiting abiotic factor hindering regeneration establishment and growth on seismic lines in treed peatlands characterized by depressed surfaces and low microtopographic complexity (Stevenson et al., 2019). In such cases, restoration treatments, such as mounding and ripping, could ameliorate microclimatic conditions by providing raised microsites with increased soil temperatures and improved moisture availability (von der Gönna, 1992; Pyper et al., 2014) and thereby promote tree regeneration on seismic lines (Filicetti et al., 2019).

Our results reveal that interactions between seismic line width and orientation affected light intensity, air temperature, and relative humidity, and abiotic changes associated with seismic lines can extend 10 m into the adjacent forest. Our study supports the recommendation to reduce seismic line width to minimize ecological changes associated with seismic line creation for oil and gas exploration (Dabros et al., 2018). Although the effects of seismic lines on the abiotic environment were generally greater on wide compared to narrow seismic lines, our results indicate that even narrow linear features (3–4 m wide) can alter abiotic conditions. The ecological footprint of seismic lines are greater

than the area of disturbance because of edge effects, which have also been observed for understory plants (Dabros et al., 2018; Finnegan et al., 2018) and overstory vegetation (Abib et al., 2019), extending into the forest. Altered microclimates on seismic lines could influence forest succession and thereby affect various ecological processes and patterns, such as the diversity, abundance, and movement of insects (Riva et al., 2018a; Riva et al., 2018b; Riva et al., 2020). Future studies should consider the cumulative effects of the presence and proximity of multiple forest edges created by various linear features, such as pipelines and roads, in fragmented landscapes. A better understanding of microclimatic conditions that promote tree regeneration on linear disturbances can contribute to improved management decisions for seismic line restoration and thereby reduce the costs for woodland caribou habitat restoration.

CRediT authorship contribution statement

Caroline M.A. Franklin: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing - original draft. **Angelo T. Filicetti:** Conceptualization, Investigation, Methodology, Writing - review & editing. **Scott E. Nielsen:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing - review & editing.

Appendix 1

Seismic line orientation, seismic line width (narrow = 3–4 m; wide = 6–8 m), year of seismic line establishment, Universal Transverse Mercator coordinates (zone = 12), and sampling information (start date, end date, and duration) for light intensity and temperature/relative humidity (temp/RH) measurements used to investigate the influence of seismic line characteristics on microclimate and tree regeneration at sites in Alberta, Canada. Sites 1–24 are seismic lines and sites W1–W3 are well pads.

Site	Orientation	Width	Established* (year)	Easting	Northing	Start date		End date		Sampling days (no.)	
						Light	Temp/RH	Light	Temp/RH	Light	Temp/ RH
1	East-west	Narrow	2005	0,463,704	6,246,371	06/07/ 2018	06/17/ 2018	06/26/ 2018	06/26/ 2018	20	10
2	North-south	Narrow	2005	0,463,740	6,246,484	06/08/ 2018	06/17/ 2018	06/26/ 2018	06/26/ 2018	19	10
3	North-south	Narrow	2005	0,464,220	6,246,853	06/15/ 2018	06/19/ 2018	07/01/ 2018	07/01/ 2018	17	13
4	North-south	Narrow	2005	0,463,797	6,246,842	06/16/ 2018	06/19/ 2018	07/01/ 2018	07/01/ 2018	16	13
5	North-south	Narrow	2005	0,463,620	6,246,678	06/17/ 2018	06/19/ 2018	07/01/ 2018	07/01/ 2018	15	13
6	East-west	Narrow	2005	0,464,123	6,248,968	06/19/ 2018	06/19/ 2018	07/01/ 2018	07/01/ 2018	13	13
7	East-west	Wide	2000–2005	0,463,879	6,245,983	06/20/ 2018	06/20/ 2018	07/01/ 2018	07/01/ 2018	12	12
8	East-west	Wide	2005–2008	0,464,460	6,236,035	07/07/ 2018	07/07/ 2018	07/22/ 2018	07/22/ 2018	16	16
9	North-south	Wide	2000–2004	0,493,479	6,254,212	07/01/ 2018	07/01/ 2018	07/16/ 2018	07/16/ 2018	16	16
10	North-south	Wide	2000–2005	0,464,263	6,241,625	07/02/ 2018	07/02/ 2018	07/16/ 2018	07/16/ 2018	15	15
11	East-west	Narrow	2005	0,464,076	6,248,613	07/06/ 2018	07/06/ 2018	07/18/ 2018	07/18/ 2018	13	13
12	East-west	Wide	1990–1999	0,463,563	6,241,552	07/06/ 2018	07/06/ 2018	07/18/ 2018	07/18/ 2018	13	13
13	East-west	Narrow	2005	0,463,823	6,246,902	07/12/ 2018	07/12/ 2018	07/25/ 2018	07/25/ 2018	14	14
14	East-west	Wide	2000–2005	0,464,190	6,245,987	07/12/ 2018	07/12/ 2018	07/27/ 2018	07/27/ 2018	16	16
15	North-south	Wide	1995–2004	0,493,475	6,253,492	07/13/ 2018	07/13/ 2018	07/27/ 2018	07/27/ 2018	15	15
16		Wide	2005–2014	0,463,734	6,245,789					13	13

(continued on next page)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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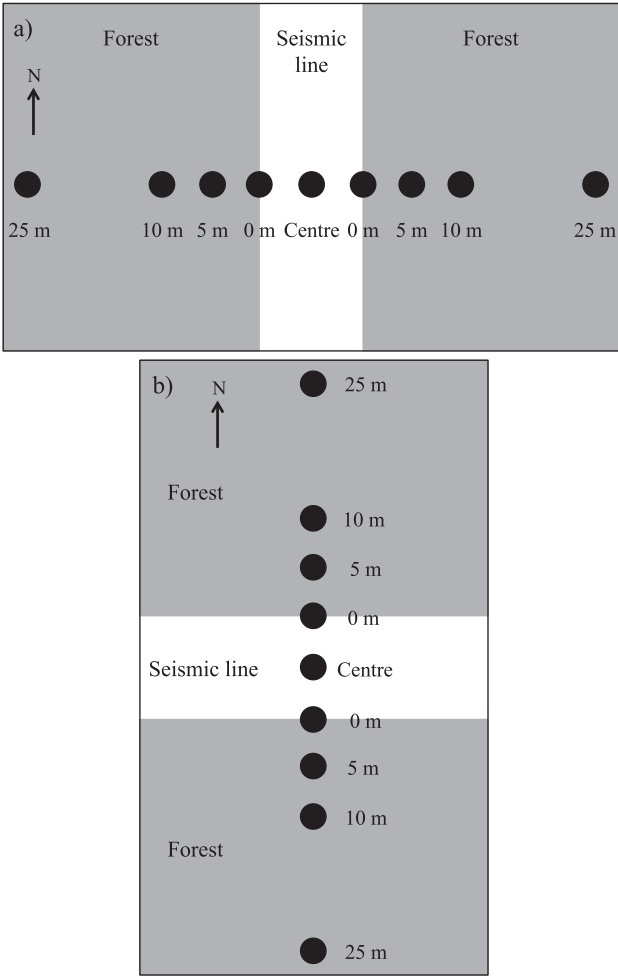
The funding sources had no involvement in the study design; in the collection, analysis, and interpretation of data; in the writing of the report; or in the decision to submit the article for publication.

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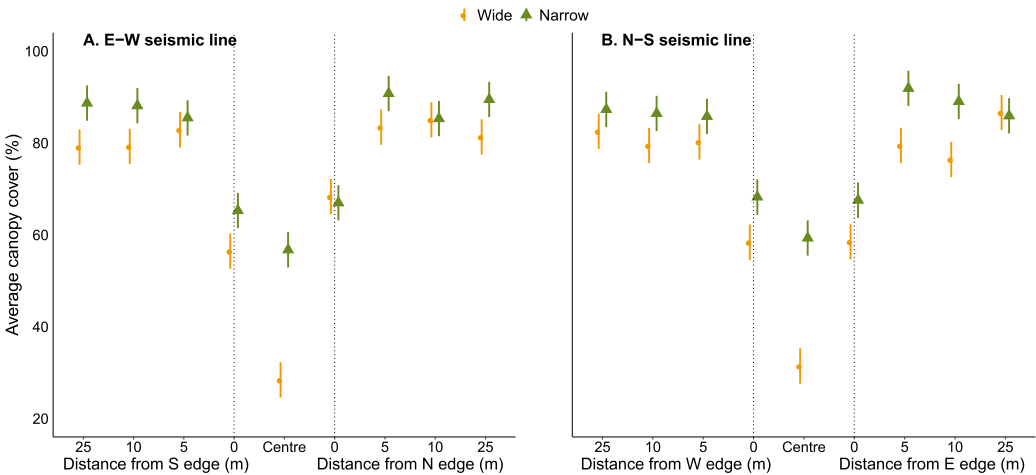
Site	Orientation	Width	Established* (year)	Easting	Northing	Start date		End date		Sampling days (no.)	
						Light	Temp/RH	Light	Temp/RH	Light	Temp/ RH
17	North-south East-west	Narrow	2005	0,464,239	6,246,905	07/19/ 2018	07/19/ 2018	07/31/ 2018	07/31/ 2018	19	19
18	North-south	Narrow	2005–2008	0,464,480	6,236,079	07/19/ 2018	07/19/ 2018	08/06/ 2018	08/06/ 2018	17	17
19	North-south	Narrow	2005–2008	0,464,433	6,235,981	07/21/ 2018	07/21/ 2018	08/06/ 2018	08/06/ 2018	17	17
20	East-west	Narrow	2005	0,463,825	6,246,996	07/25/ 2018	07/25/ 2018	08/06/ 2018	08/06/ 2018	13	13
21	North-south	Wide	2005	0,493,075	6,253,640	07/25/ 2018	07/25/ 2018	08/07/ 2018	08/07/ 2018	11	11
22	East-west	Wide	2000–2005	0,464,841	6,245,972	07/29/ 2018	07/29/ 2018	08/07/ 2018	08/07/ 2018	10	10
23	North-south	Wide	1995–2004	0,493,480	6,253,042	07/30/ 2018	07/30/ 2018	08/07/ 2018	08/07/ 2018	9	9
24	East-west	Wide	1990–1999	0,463,991	6,241,534	08/03/ 2018	08/03/ 2018	08/07/ 2018	08/07/ 2018	5	5
W1	–	–	–	0,463,493	6,250,587	06/10/ 2018	06/21/ 2018	07/03/ 2018	07/03/ 2018	24	13
W2	–	–	–	0,464,204	6,247,832	07/06/ 2018	07/06/ 2018	07/22/ 2018	07/22/ 2018	17	17
W3	–	–	–	0,463,730	6,247,109	07/25/ 2018	07/25/ 2018	08/06/ 2018	08/06/ 2018	13	13

*Based on estimates provided by [Nash \(2011a; 2011b\)](#) and satellite imagery in Google Earth. Year ranges indicate time period during which seismic line was probably cleared.

Appendix 2. Schematic of sampling design used for measuring abiotic variables (light intensity, air temperature, relative humidity) and tree regeneration density on seismic lines orientated a) north–south and b) east–west in Alberta, Canada. Black circles represent sampling locations and distances refer to distance from the seismic line-forest edge. Diagram is not to scale.



Appendix 3. Average canopy cover (estimated marginal means \pm standard error) on seismic line centres and at four distances from wide (6–8 m) and narrow (3–4 m) seismic line-forest south (S), north (N), west (W), and east (E) edges in Alberta, Canada. Values represent results from a mixed model with Gaussian distribution created using the lmer function in the lme4 package (Bates et al., 2019). Site was a random effect.



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