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Low-impact line construction retains and speeds recovery of trees on seismic lines in forested peatlands

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Abstract

Seismic lines are linear features created by the oil and gas industry for energy exploration. Though individually narrow, collectively seismic lines are a pervasive management challenge, resulting in changes to biogeochemical cycles, plant and animal abundance and behaviour, predator–prey relationships, and forest successional trajectories. These impacts arise from historical construction methods that used bulldozers to remove vegetation and substrate leaving lines as persistent openings in a state of arrested succession. In the mid-1990s, "low-impact seismic" (LIS) line construction began, using mulchers to remove vegetation aboveground to minimize impacts and hasten reforestation. Here, we evaluated the effectiveness of LIS in retention, recruitment, and growth of seedlings in forested peatlands in northeast British Columbia. Retained and recruited trees on LIS lines were found at 69% and 64% of sites, had mean densities of 3400 and 6000 stems/ha, and mean heights of 42 and 11 cm, respectively. These LIS lines appeared to recover along expected trajectories toward tree cover, thereby mitigating challenges typical of older seismic exploration. Our results suggest it is feasible to further fast-forward line recovery by ensuring mulcher drums are kept as high as possible to increase the number and height of trees through the mulching process.

Key words: seismic line, linear disturbance, boreal forest, forest gap, disturbance recovery

1. Introduction

Seismic lines (hereafter lines) are narrow linear features (<1 to ∼10 m wide) cut into forests where access is needed to sample, image, and interpret the subsurface, often in support of the exploration and production (E&P) of hydrocarbons. E&P is widespread across western Canada, especially in Saskatchewan, Alberta, British Columbia, and the Northwest Territories. In these densely forested boreal and mountain ecosystems, seismic lines are ubiquitous (Pasher et al. 2013; Dabros et al. 2018) and a persistent management challenge (Nagy-Reis et al. 2021). A wide body of literature describes impacts of lines to wildlife behaviours and populations (Northrup and Wittemyer 2013; Dabros et al. 2018), and to fundamental ecological processes like carbon, methane, and water cycling (Williams et al. 2013; Strack et al. 2019; Davidson et al. 2020), fire dynamics (Deane et al. 2020; Riva et al. 2020), forest succession (Lee and Boutin 2006; Finnegan et al. 2018, 2019; Barber et al. 2021), predator–prey relationships (DeMar and Boutin 2018), and species assemblages of vegetation, animals and insects (Dawe et al. 2017; Dabros et al. 2018; Fisher and Burton 2018; Riva et al. 2018).

In part, the management challenges of lines in forested landscapes stem from their persistence as open (unforested) disturbances that remain distinct from their surroundings. Seismic exploration became widespread in Canada by the early 1950s (Rintol 2007); until the early mid-1990s, lines were created using bulldozers to scrape away vegetation and the surface soil substrate to create flat, smooth work surfaces navigable by a pickup truck ("conventional" or "legacy" lines in the literature) (Alberta Environment and Parks 2021). Especially in forested peatlands, those practices removed soil horizons and surface microtopography needed to modulate water and temperature gradients required for germination and growth of tree species (Braverman and Quinton 2016; Stevenson et al. 2019; Davidson et al. 2020; Filicetti and Nielsen 2020). As a result, conventional lines often recover to steady states dominated by something other than tree cover (e.g., graminoid or shrub species), sometimes for decades beyond expected successional trajectories for a forested peatland disturbance regime (Lee and Boutin 2006; van Rensen et al. 2015; Finnegan et al. 2018, 2019; Dabros et al. 2022). Indeed, a primary strategy of current line restoration is to recreate microtopography and reintroduce tree seedlings to reforest lines more quickly (Filicetti et al. 2019; Pyper and Broadley 2019; Dickie et al. 2022).

Beginning in the mid-1990s, the E&P industry began experimenting with alternative "low-impact seismic" (LIS) line preparation methods (Fig. A1). These efforts were driven in part by: (i) regulatory pressure to "do something" to speed recovery of trees (Alberta Environment and Parks 2021) and (ii) findings from the Arctic that showed reduced disturbance during line construction sped recovery to expected plant communities and cover (Hernandez 1973; Felix and Raynolds 1989; Emers et al. 1995). By the mid-2000s, mulchers emerged as the primary tool to create LIS lines. A mulcher is designed to chip standing vegetation above the ground surface and to minimize disturbance to the substrate, and mulching drums can be elevated and lowered during operation to respond to changing ground and vegetation conditions.

Whether mulching expedites recovery of trees along LIS lines has not yet been evaluated. General assessments of vegetation to mulching show changes to vegetation communities along lines and altered forest dynamics at seismic line edges (Kansas et al. 2015; Dabros et al. 2017; Franklin et al. 2021; Echiverri et al. 2022), though those works did not explicitly measure online tree response, per se. However, anecdotal evidence and grey literature suggest mulched LIS lines recover more quickly to tall woody shrubs compared to conventional lines (Tigner et al. 2016). Regardless, mulching has become standard practice in E&P regulations despite a lack of knowledge in its efficacy toward mitigating ecological impacts. For example, regulations in all western Canadian jurisdictions require lines to be mulched to minimize ground disturbance without further specificity for operational use, like prescriptive mulcher drum height, thereby leaving operational use open to interpretation (e.g., *Alberta*: Government of Alberta 2006, 2021, 2022; *British Columbia*: BC Oil and Gas Commission 2021, 2022; *Northwest Territories*: Government of the Northwest Territories 2015; Mackenzie Valley Land and Water Board et al. 2021; *Saskatchewan*: SMEGAC 2016; *Yukon Territory*: Government of Yukon 2006, 2015). Understanding the relationships between mulching practices, the subsequent impacts to the ground substrate and microtopography, and persistence and recovery of trees along mulched lines is important because changing dynamics of E&P have triggered the construction of more lines, in higher densities, in the last decade in Canada (Chopra and Marfurt 2012; Schulte and Manthei 2014; Nagy-Reis et al. 2021).

Here we conducted a mensurative experiment to evaluate the response of trees along mulched LIS lines in forested peatlands in northeast British Columbia. Our goal was to understand whether mulching expedited recovery of trees along lines, and whether the height of the mulcher drum above the ground improved tree recovery. Specifically, we evaluated the influence of mulcher drum height during line construction on retention and recruitment of conifer trees 1 to 11 years after line construction using a series of predictor variables that described impacts to the substrate or competition. Retained trees were those that persisted through the mulching process, while recruited trees were those that germinated since lines were mulched. If mulching of LIS lines retained trees and promoted faster recovery of conifer seedlings or new tree recruitment, then directives for operational use of mulchers could be refined to improve recovery outcomes for LIS lines and thereby potentially reducing future restoration needs that are expensive and variable in success (Filicetti et al. 2019; Yemshanov et al. 2019).

2. Methods

2.1. Study area

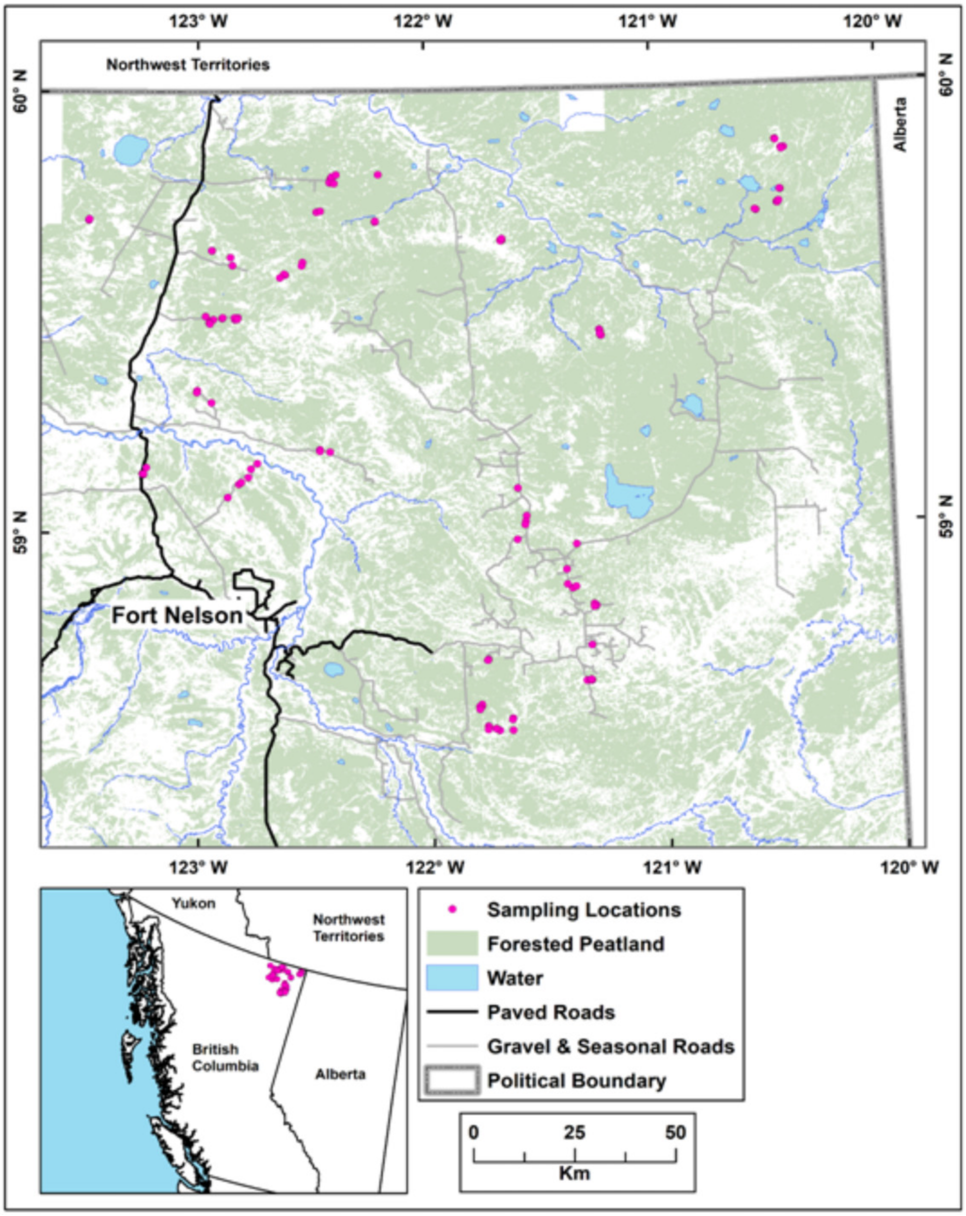
The study encompassed ∼19 000 km^2 area near Fort Nelson in northeast British Columbia (NE BC), Canada (Fig. 1). The region is in the Moist Cool Boreal White and Black Spruce biogeoclimatic zone (BWBSmk; DeLong et al. 2011), characterized by long snowy winters and short rainy summers (averaging 1900 mm snow, 300 mm rain, and <125 frost-free days per year, based on 1971–2010 historical climate data available from Government of Canada (2023)). The study area is mostly flat and covered by extensive forested peatlands of *Sphagnum*-based soils and stands of pure black spruce (*Picea mariana* (Mill.) B.S.P.) or black spruce with a small component of tamarack (*Larix laricina* (Du Roi) K. Koch). Pure stands of tamarack are small and uncommon in this system and were not sampled for this study. Forested peatlands are interspersed with open and shrub-dominated wetlands and waterbodies, and peatlands are occasionally interspersed by upland forests with mineral soils, especially along river valleys and in undulating terrain (Filicetti et al. 2019; Filicetti and Nielsen 2020).

2.2. Site selection

We stratified field sampling locations in a Geographic Information System (GIS; ArcGIS 10.4, ESRI, Redlands, California) using spatial data on land cover classes and seismic lines. First, we reclassified British Columbia Vegetation Resources Inventory (VRI), a polygon-based, stand-scale land cover inventory, into forested peatland and all other cover types using tree species and soil types (moisture regime) at the stand scale (Ministry of Forests 2016). Next, we used geophysical spatial data (i.e., seismic line footprint) managed by the BC Oil and Gas Commission (BCOGC) (BC Oil and Gas Commission 2016) and seismic line cut summary data used to calculate Timber Damage Assessments (TDA; made available by the BCOGC upon request) to identify individual seismic exploration programs and construction dates and to identify lines as newly mulched (e.g., the mulching event was the first industrial, anthropogenic disturbance event) or existing (e.g., the mulching event reopened a previous exploration line or other disturbance). In some cases, individual seismic lines and entire seismic programs are reopened to recollect seismic exploration data. We used data for lines cut in 2005 (2004–2005 winter operating season) or after because that was when use of mulchers was exclusive (earliest reported use of mulchers in the study area was the 1999–2000 winter operating season). We sampled only newly mulched LIS lines (hereafter mulched lines).

We then selected a set of a priori sampling sites along mulched lines constructed between the 2004–2005 through the 2014–2015 winter operating season (excluding 2013–2014 due to low availability; no seismic programs were shot in 2015–2016) outside of upland forest types. In those years mulched lines ranged from 1.3 to 6.2 m wide, though widths typically decreased over time to ∼ 2 to 3 m wide, which remains the standard width range for mulched lines across Canada. Current E&P typically mulch lines in a grid pat-

Fig. 1. Locations of sample sites used to evaluate tree recovery along mulched, low-impact seismic (LIS) lines in northeast British Columbia (NE BC), Canada. All lines were originally mulched during the winter operating season (December–March) between 2004–2005 and 2014–2015, and responses in trees collected in the field in the summer 2016. Forested peatland was derived from BC Vegetation Resource Invenotry data (https://www.bcogris.ca/projects/natural-recovery-on-low-impact-seismic-lines-in-northeast-bc/); shapefiles for roads are available from the BC Oil and Gas Commission (https://data-bc-er.opendata.arcgis.com/search?tags=OD_Roads).



tern orientating lines north–south and east–west; in rare cases, mulched lines are orientated differently relative exploration needs. Winter operating season means that seismic programs were conducted during snow-covered and frozen ground conditions with mulching occurring typically from mid-December through mid-February. For each operating season, we located candidate sites in >1 seismic program to prevent confounding results by operator practice or localized ecotype. Within a program, we located one site per seismic line and VRI polygon where feasible, but in several cases had to place multiple sites along the same line in different polygons or in the same polygon along different lines. We sampled an even number of sites across available line widths and line bearings per year, though lines became increasingly narrow over time. In all cases, we sampled sites in treed bogs based on site classification using the British Columbia Ecosystem Classification System (DeLong et al. 2011) (Fig. A1).

2.3. Field methods

We collected field data between July and August 2016 using a hierarchical sampling design. At each sampling site, we established a 100 m long plot into which we nested three, 2 × 2 m (4 m^2) quadrats. We placed one quadrat at metres 1, 50, and 99 of the 100 m long plot (n = 108 plots; 324 quadrats). Plots were the width of the sampled lines. Ultimately, we were interested in understanding the relationship between the height of the mulcher drum and the occurrence, density, and height of retained and recruited conifer trees along mulched lines. Because line recovery can be inconsistent even at very fine spatial scales (Filicetti et al. 2019; Filicetti and Nielsen 2020), we considered individual quadrats as the sample unit for analyses but treated the plot scale as a random effect.

At the plot, we confirmed the cut type, line age, and whether a line was new or existing using seismic shot tags attached to trees during seismic exploration field operations. We also measured the proportion of disturbed substrate as damaged moss, disturbed or flatted microtopography, or rutted or exposed ground as percentage cover from 0% to 100%; line widths to the nearest centimeter; and line bearings to the nearest degree. We categorized the distribution and pattern of deposited mulch as continuous (e.g., a continuous garden pathway) or scattered (e.g., discrete clumps interspersed by uncovered ground). Lastly, we searched along the line for evidence of continued human use for trapping or other travel (e.g., tracks or depressions, trapping boxes, cut limbs, etc.) up to 1 km from plots. Other studies indicated that continued recreational use of lines can keep them open, (Pigeon et al. 2016), but in this study we found no evidence of continued use.

At the quadrat scale, we measured the height of trees to the nearest half-centimeter and aged all conifer stems by counting whorls and adding a constant of 1 to account for the first year of growth. We differentiated conifers as retained if the determined tree age was greater than the line age (e.g., persisted through the mulching event) or recruited if the determined tree age was less than the line age (e.g., new since the mulching event). We also measured adjacent stand height using a clinometer and adjacent canopy cover using a concave densiometer, depth to the water table in centimeters using a planting spade to dig a small pit (up to 100 cm), and we inventoried all live stems of shrub species ≥0.5 m in height and calculated a stem density within the quadrat (Tables A1 and A2).

Mulcher drum height is not a regulated requirement of a seismic application in BC, and drum heights are not recorded. Here we used two proxies for drum height: (i) "snow depth" as the depth of accumulated precipitation, in millimeters, averaged from three provincial meteorological stations in the study area (FLNRO_WMB Stations 599, Fort Nelson FS; 119, Nelson Forks; and 117, Sierra) (PCIC 2022) between December and February, inclusive, calculated at the year of line construction; and (ii) "stump height" as the average height of mulched tree stems as measured in the field, to the nearest centimeter. We measured stump height of the most frequently observed height (based on visual assessment) along the 100 m plot to the nearest centimeter. Importantly, we are not comparing the efficacy of these proxies, rather using them as alternative estimates of drum heights during line construction. Neither proxy provides a precise height, but both represent a relative elevation above the ground surface that is operationally relevant. We believe snow depth represents a "ceiling" that is the farthest above the ground surface a mulcher could feasibly operate, and stump height represents a "floor" height below which a mulcher could not have removed vegetation. The two proxies are only moderately correlated with a Pearson's correlation coefficient between snow depth and stump height of 0.49 and thus represent similar but still distinct proxies.

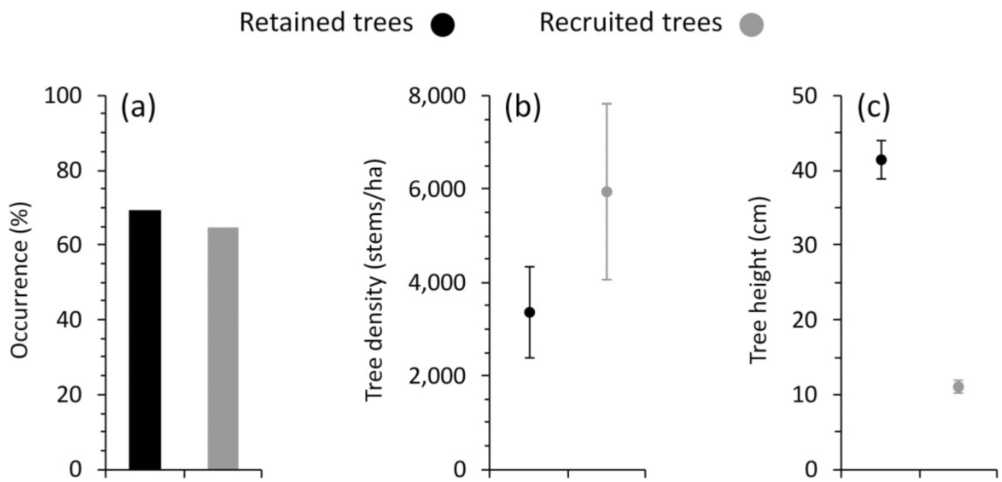
2.4. Analysis

We analyzed occurrence, density, and height of trees on seismic lines at the scale of the quadrat using a similar workflow. We also analyzed retained and recruited trees separately to better understand recovery dynamics. Therefore, we have six response variables: (i) retained tree occurrence, (ii) recruited tree occurrence, (iii) retained tree density, (iv) recruited tree density, (v) retained tree height, and (vi) recruited tree height. We first visualized these response variables by plotting the overall occurrence, mean density, and mean height for retained and recruited trees separately.

We then analyzed these data in a two-step (Hurdle) process: (i) we first used all quadrats for tree occurrence and (ii) we then removed all quadrats with no trees present (zero) to fit models for tree density and height when present (McCullagh and Nelder 1989; Nielsen et al. 2005). Here, zeroes are true zeroes from the same source, driven by ecological restrictions that we have included as predictor variables, necessary for this two-step process (Rose et al. 2006; Blasco-Moreno et al. 2019; Feng 2021). Furthermore, this design more easily highlights potential differences in response to predictor variables on occurrence (presence/absence) and that of density given occurrence.

Specifically, we used a mixed-effects logistic model (*xtlogit* command in STATA 15.1/SE; StataCorp. 2017) for tree occurrence, mixed-effects negative binomial models (*xtnbreg* command in STATA 15.1/SE; StataCorp. 2017) for tree density, and linear mixed-effects models (xtreg command in STATA 15.1/SE; StataCorp. 2017) for tree heights using a $\log_{10}$ transformation to meet model assumptions. We started all models with the full suite of predictor variables and used backward selection, retaining significant (p < 0.05) variables, to generate the simplest explanatory models for each of the six response variables. The predictor variables we used were: (i) snow depth proxy for drum height, (ii) stump height proxy for drum height, (iii) line age, (iv) line bearing, (v) continuous mulch, (vi) depth to water table, (vii) disturbed substrate, (viii) line width, (ix) adjacent canopy cover, (x) adjacent stand height, (xi) retained tree density (for recruited trees only), and (xii) shrub density (Tables A1, A2, and A3). Not only we report coefficients (β) for all models, but we also interpret the coefficients as percentage change per one unit change in the predictor variable using the formulas $\{1/[1 + \exp(-1\times(\beta))]\}\times 100\%$; $\{[\exp(\beta)-1]\times 100\%\}$; and $\{[10^{(\beta)}-1]\times 100\%\}$ for tree occurrence, density, and height, respectively.

Fig. 2. Occurrence (*a*), density (*b*), and height (*c*) of retained and recruited trees on mulched, low-impact seismic (LIS) lines across years since disturbance in forested peatlands in northeast British Columbia (NE BC), Canada. Error bars are represented by 95% confidence interval.



3. Results

3.1. Field-measured tree occurrence, density, and height on low-impact seismic lines

We found at least one retained and one recruited tree in 69% and 64% of the sampled sites, respectively. We also found that 82% of sites had at least one retained or recruited tree and 51% of sites had both retained and recruited trees. Retained tree density ranged from 0 to 32 000 stems/ha ($\bar{x}$ = 3400; SE = 500) and recruited tree density ranged from 0 to 50 000 stems/ha ($\bar{x}$ = 6000; SE = 1000). Retained tree height ranged from 3 to 180 cm ($\bar{x}$ = 42; SE = 1.37) and recruited tree height ranged from 0.5 to 140 cm ($\bar{x}$ = 11; SE = 0.4), Fig. 2.

3.2. Patterns in tree occurrence on low-impact seismic lines

The final model for retained trees included both proxies for drum height, line width, adjacent canopy cover, and shrub density. Occurrence of retained trees increased 0.61% per 1 cm increase in snow depth and increased 0.9% per 1 cm increase in stump height. Occurrence of retained trees decreased 9.3% per 1 m increase in line width; decreased 1.0% per 1% increase in adjacent canopy cover; and decreased 0.8% per increase in 1 shrub stem per quadrat (Table 1 and Fig. 3).

The final model for recruited trees included continuous mulch, adjacent canopy cover, line age, shrub density, and retained tree density. Neither proxy for drum height explained the occurrence of recruited trees. Occurrence of recruited trees decreased 26.9% where continuous mulch occurred; decreased 1.4% per 1% increase in adjacent canopy cover; increased 10.0% per 1 year increase in line age; decreased 1.8% per increase in 1 shrub stem per quadrat; and was quadratically related to retained trees, specifically, occurrence was predicted to be 0% at 0 retained trees per quadrat, increased to a peak of 38.0% at 10 retained trees per quadrat, and declined to 0.4% at 20 retained trees per quadrat (Table 1 and Fig. 3).

Table 1. Mixed-effects logit regression model parameters (coefficient, β; and standard error, SE) relating tree occurrence to proxies of mulcher drum height (snow depth and stump height), continuous mulch presence, line width, adjacent canopy cover, line age, shrub density, and retained tree density (for recruited trees only), in northeast British Columbia, Canada.

Tree occurrence	Retained	Recruited
Constant	−0.14 (0.51)	−2.17 (0.71)**
Proxies for mulcher drum height		
Snow depth	0.02 (0.01)*	
Stump height	0.04 (0.01)*	
Line characteristics		
Age		0.41 (0.09)***
Continuous mulch		−1.20 (0.46)**
Width	−0.38 (0.14)**	
Vegetation variables		
Adjacent canopy cover	−0.04 (0.01)**	−0.06 (0.02)**
Retained tree density		0.40 (0.13)**
Retained tree density^2		−0.02 (0.01)**
Shrub density	−0.03 (0.01)*	−0.07 (0.02)**
Model statistics		
n	324	324
Wald χ^2	38.12	43.52
Prob > χ^2	< 0.001	< 0.001

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$.

3.3. Patterns in tree density on low-impact seismic lines

The final model for retained trees included the snow depth proxy for drum height. Density for retained trees increased by 1.3% per 1 cm increase in snow depth (Table 2 and Fig. 4).

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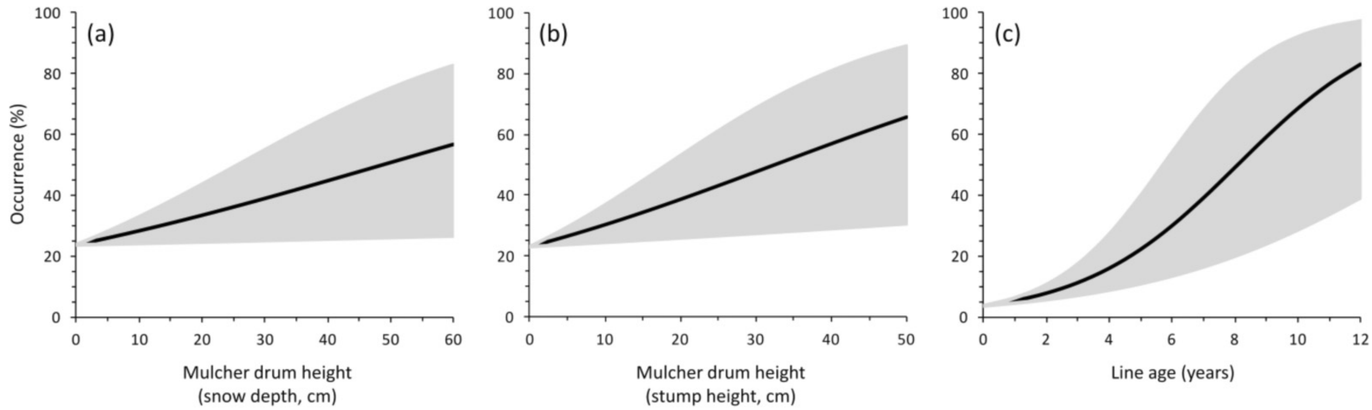
Fig. 3. Predicted occurrence of retained trees based on predictor variable proxies for mulcher drum height snow depth (*a*) and stump height (*b*), and recruited trees based on predictor variable line age representing time since disturbance (*c*) in forested peatlands in northeast British Columbia (NE BC), Canada. The black line represents the average predicted occurrence and the gray area the 95% confidence interval.



The final model for recruited trees included line width, line age, and retained tree density. Neither proxy for drum height explained recruited tree density. Density of recruited trees increased by 33.3% per 1 m increase in line width; increased 13.0% per 1 year increase in line age; and was quadratically related with retained trees, specifically, density was predicted to have no change at 0 retained trees per quadrat, increased to a peak of 102.2% at 13 retained trees per quadrat, and declined to 63.7% at 20 retained trees per quadrat (Table 2 and Fig. 4).

3.4. Tree height patterns on low-impact seismic lines

The final model for retained trees included the snow depth proxy for drum height, line age, and shrub density. Height for retained trees increased 1.2% per 1 cm increase in snow depth; was quadratically related to line age, specifically, height was predicted to have no change at 0 years, increased to a peak of 63.2% at 9 years, and declined to 56.9% at 12 years; and increased 2.5% per increase in 1 shrub per quadrat (Table 3 and Fig. 5).

The final model for recruited trees included line bearing, line age, adjacent stand height, and shrub density. Neither proxy for drum height explained recruited tree height. Height of recruited trees decreased 26.0% along north/south-orientated lines when compared to east/west-orientated lines; increased by 9.0% per 1 year increase in line age; decreased by 8.6% per 1 m increase in adjacent stand height; and was quadratically related to shrub density, specifically, height was predicted to increase by 0% at 0 shrubs per quadrat, increased to a peak of 28.3% at 18 shrubs per quadrat, and declined to 15.8% at 30 shrubs per quadrat (Table 3 and Fig. 5).

Table 2. Mixed-effects negative binomial regression model parameters (coefficient, β; and standard error, SE) relating tree density per 4 m^2 to a proxy of mulcher drum height (snow depth), line width, line age, and retained tree density (for recruited trees only), in northeast British Columbia, Canada.

Tree density (stems/4m^2)	Retained	Recruited
Constant	0.84 (0.3)**	−0.79 (0.4)*
Proxies for mulcher drum height		
Snow depth	0.013 (0.005)**	
Line characteristics		
Age		0.12 (0.03)***
Width		0.29 (0.06)***
Vegetation variables		
Retained tree density		0.11 (0.04)**
Retained tree density^2		−0.004 (0.002)*
Model statistics		
n	128	140
Wald χ^2	7.48	37.38
Prob > χ^2	0.006	< 0.001

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

4. Discussion

We found that use of mulching to construct LIS lines provides a clear mitigation benefit, influencing both the immediate retention and recruitment, and the longer-term persistence of conifer trees along lines. The majority (>64%) of sampled lines supported retained and recruited trees, demonstrating that existing trees can persist through mulching events and that new trees can establish along mulched lines. Further, we observed that mean tree occurrence, density, and height all increased over the 11 sampled years after line construction demonstrating that new trees continued to germinate and that established seedlings continued to grow. Both outcomes are in sharp contrast to previous studies showing recovery of conventional seismic lines in peatlands often stalled in an arrested state supporting few, if any, mature trees even decades after line construction (Lee and Boutin 2006; Van Rensen et al. 2015; Finnegan et al. 2018; Dabros et

Fig. 4. Predicted tree density of retained trees based on predictor variable proxy for mulcher drum height snow depth (*a*), and recruited trees based on predictor variable line age representing time since disturbance (*b*) in forested peatlands in northeast British Columbia (NE BC), Canada. The black line represents the average predicted occurrence and the gray area the 95% confidence interval.

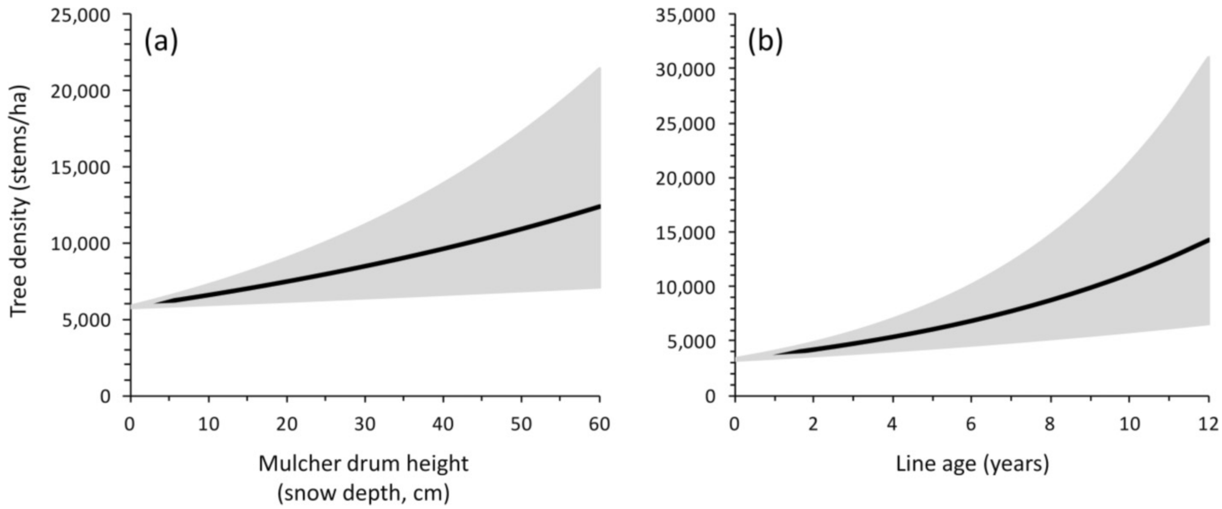


Table 3. Mixed-effects regression model parameters (coefficient, β; and standard error, SE) relating tree height ($\log_{10}$ transformed) to a proxy of mulcher drum height (snow depth), line bearing, line age, adjacent stand height, and shrub density, in northeast British Columbia, Canada.

Tree height (cm)	Retained	Recruited
Constant	0.96 (0.13)***	0.89 (0.12)***
Proxies for mulcher drum height		
Snow depth	0.005 (0.001)***	
Line characteristics		
Age	0.10 (0.04)*	0.04 (0.01)**
Age^2	−0.01 (0.003)*	
Bearing		−0.13 (0.06)*
Vegetation variables		
Adjacent stand height		−0.04 (0.01)**
Shrub density	0.011 (0.002)***	0.03 (0.01)**
Shrub density^2		−0.0007 (0.0003)**
Model statistics		
n	128	140
LR χ^2	27.96	30.04
Prob > χ^2	< 0.001	< 0.001

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

al. 2022). Together, our observations suggest that mulching can expedite conifer recovery along seismic lines in forested peatlands by immediately aligning recovery trajectories toward a reforested state.

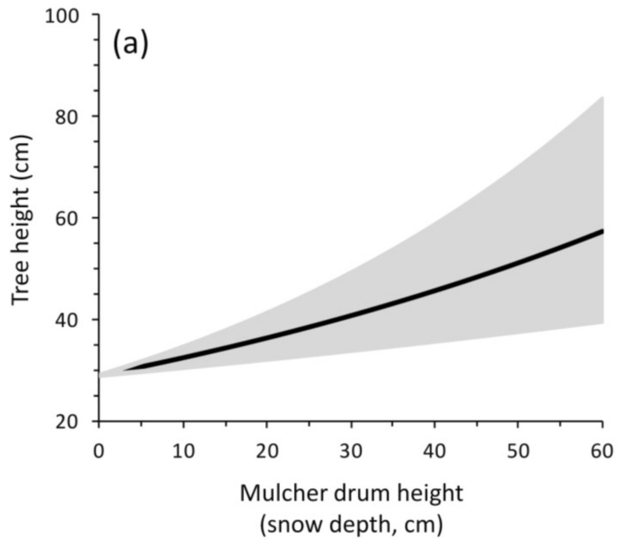
Importantly, our data also show that increasing the height of the mulcher drum during creation of mulched LIS lines can likely further enhances conifer recovery outcomes. We observed a significant positive relationship between the measured proxies of drum height and the occurrence, density, and height of retained trees. Thus, when mulcher drums removed vegetation further away from the ground surface, more lines retained more and taller trees. This increased the stocking density and the heights of retained trees at the start of line recovery. The predicted relationship between drum height proxies and retained tree occurrence, density, and height was linear, suggesting a continuously increasing benefit.

Mulching appeared to preserve the ability of most lines in treed peatlands to support tree recovery akin to other boreal disturbances like fire and timber harvest (Bergeron and Dubue 1988; Harper et al. 2016). Our data show that most sampled lines did not sustain disturbances to important features like bryophyte cover and microtopography, so broadly speaking, elevating mulcher drums to at a minimum of above the tops of hummocks is likely to preserve the conditions suitable for conifer recruitment and their continued growth (Caner and Lieffers 2014; Lieffers et al. 2017). There is similar evidence from forestry applications that mulching can effectively retain tree seedlings through mid- and overstory removal (Brockway et al. 2009; Pile et al. 2017; Lee et al. 2019), facilitate continued growth of retained seedlings (Sanchez and Eaton 2001), and reverse altered stand-level succession (Smith et al. 2020). Detailed measurements of soil and substrate response to mulching could improve our understanding of these processes, and help refine directives for operational use of mulchers, especially around how much ground disturbance can be tolerated before conifer growth is negatively impacted.

4.1. Field-measured tree occurrence, density, and height on low-impact seismic lines

We found that the majority of sites had retained and/or recruited trees. Observed tree densities were high, averaging 3400 and 6000 stems/ha for retained and recruited trees, respectively. This density surpasses current reforestation and

Fig. 5. Predicted tree height of retained trees based on predictor variable proxy for mulcher drum height snow depth (*a*), and recruited trees based on predictor variable line age representing time since disturbance (*b*) in forested peatlands in northeast British Columbia (NE BC), Canada. The black line represents the average predicted occurrence and the gray area the 95% confidence interval.



line reclamation guidance (Government of Alberta 2017; Alberta Agriculture and Forestry 2018), where it exists (currently, Alberta is the only province with a seismic line recovery framework). Observed tree heights averaged 42 and 11 cm for retained and recruited trees, respectively. While these average heights do not specifically meet current advanced regeneration requirements (e.g., 60 to 65 cm after 8 to 10 years; Government of Alberta 2017), many individual trees did surpass prescribed height requirements (Fig. 2*c* and Table A3). Recovery to tree cover is not the only metric of line recovery or restoration success; however, that goal currently underlies the management focus for seismic lines in western Canada (Government of Alberta 2017; Filicetti et al. 2019; Pyper and Broadley 2019; Dickie et al. 2022).

4.2. Patterns in tree occurrence on low-impact seismic lines

Apart from drum height, adjacent canopy cover, shrub density, and line width all decreased the occurrence of retained trees along sampled lines. Because occurrence of retained trees is a measure of tree persistence through a mulching event, it is unlikely these factors are related to ecological processes like shading, competition, or a lack of colonizable surface area (Filicetti and Nielsen 2020, 2022; Filicetti et al. 2021). Instead, this is likely an artifact of operations and logistics. A line is mulched to provide access to subsequent phases of an operation; in densely forested peatlands and along wider lines, more intensive mulching is required to appropriately clear access. In both cases, the likelihood standing trees are removed during line construction increases.

Occurrence of recruited trees decreased with continuous mulch deposition likely because too much mulch may limit the amount of colonizable surface area along lines (Filicetti et al. 2021). Raising mulcher drums could create less woody material; however, the amount of mulch created is ultimately driven by the standing biomass of the forested stand. We found that less than a third of our sampled sites had continuous mulch, so in the open, boreal forested peatlands across most of northwestern Canada, we believe e issue of continuous mulch limiting tree occurrence is not widespread. Adjacent canopy cover and shrub density were inversely related to occurrence of recruited trees, likely due to increased competition and shading (Filicetti and Nielsen 2020, 2022).

4.3. Patterns in tree density on low-impact seismic lines

Our finding that proxies for drum height were positively related to retained tree density is not surprising; a higher mulcher drum retains more trees already growing on lines. Line width was positively related to the density of recruited trees, likely because wider lines allow more sunlight to reach the ground (Stern et al. 2018; Franklin et al. 2021). Line age also increased the density of recruited trees demonstrating, again, that mulched lines recruit trees over time and are not in an arrested state.

4.4. Tree height patterns on low-impact seismic lines

We found that proxies of drum height were positively related to retained tree height. Many retained trees were quite tall (Fig. 2*c* and Table A3) suggesting mulchers do not uniformly remove all vegetation along lines. Young trees are pliable and some are likely pushed down rather than cut off during mulching. Elevating a mulcher drum likely pays "outsized dividends" by increasing the retention of taller, pushed over trees.

For recruited trees, a north/south line bearing produced shorter trees than an east/west bearing. Other studies have shown similar recovery patterns relative to line orientation, likely because shading along that orientation limits availability of sunlight to young seedlings (van Rensen et al. 2015; Stern et al. 2018; Franklin et al. 2021). Similarly, adjacent stand height was negatively related to recruited tree height as it limits the sunlight reaching the ground (Filicetti and Nielsen 2018). Shrub density had a quadratic relationship with the height of recruited trees, where tree height increased initially with increasing shrub density but then decreased as shrub density continued to increase. This suggests a threshold effect for competition beyond which high stem density limits tree growth (Lieffers et al. 1999; McCarthy 2001; Chen and Taylor 2012). This is important when considering continued tree recovery and stand succession beyond our 11-year sampling timeframe. If mulching cannot adequately reduce long-term competition from shrubs, initial recovery success of conifers observed in this study could dissipate as faster growing shrubs outcompete slower growing conifers (McCarthy 2001; Chen and Popadiouk 2002), thereby stalling recovery as has been observed along seismic lines elsewhere (Lee and Boutin 2006; van Rensen et al. 2015; Finnegan et al. 2018, 2019; Dabros et al. 2022).

5. Management implications

Our results suggest that current regulatory requirements should strive to elevate mulching drums above the ground surface as much as possible to preserve surface microtopography, retain small trees, and facilitate tree recruitment. This simple mitigative action may improve conifer recovery along mulched lines and reduce further restoration needs. However, growth of trees in boreal ecosystems is a slow process and recovery to forest conditions can take decades to achieve (Bergeron and Dubue 1988; Chen and Popadiouk 2002). Because retained trees continue to grow over time, mulching of seismic lines, especially with elevated mulching drums, can fast-forward the recovery of conifers by several decades. Although we show that other factors do influence line recovery, increasing drum elevation is the most logistically feasible because it is controllable during operations. Seismic exploration is focused on the subsurface and cannot effectively avoid all land covers that are slow to recover once disturbed. By elevating mulching drums, it is feasible to expedite tree recovery in forested peatlands even when they cannot be avoided.

It is important to reiterate that we did not explicitly measure the elevation of the mulching drum above the surface of the ground during line construction. Instead, we used snow depth and stump height as proxy estimates for drum height. The proxy for snow depth was retained more frequently in models than the proxy for stump height, perhaps suggesting that environmental conditions (snow) was more effective at maintaining drum height than operator decisions. While our intent was not to compare those proxies, operationally this means that in years with deeper snowpack or during later parts of a winter season when more snow has accumulated, there is likely an increased buffer between mulcher drums and the ground. There is evidence from the Arctic that snow depth can buffer impacts to vegetation and the substrate along conventional seismic lines (Felix and Raynolds 1989). This also means that operations can mimic and enhance observed mitigations even during years of low snowpack simply by further elevating the mulching drums.

Our results indicated that mulching LIS lines can improve the natural recovery of trees in forested peatlands and that increasing the height of mulching drums further improves those recovery outcomes. Ultimately the management question is how high is high enough? From a tree recovery perspective, the answer is always that higher is better. However, practically, when considering all facets of an operation (e.g., subsequent use of lines to acquire seismic data, worker safety, etc.) there is an elevation at which a drum is too high for operational use. A precise drum elevation is beyond the scope of this study because it depends on operational workflows, field personnel, and logistics, as well as forest types and ground conditions. Here, we focused on treed bogs and it is possible that trees in fens and other forested peatlands respond differently to mulching and drum heights. However, sufficient information about forest types and local conditions are available throughout western Canada where seismic operations occur to make site- and project-specific estimates about how high a mulcher drum should be above the ground to retain not just hummocks and microtopography, but also trees. Constructing linear disturbances by mulching with a highly elevated drum has the potential to save billions of dollars, ranging from \$4000 to \$18 000 per km, in restoration costs (Filicetti et al. 2019; Yemshanov et al. 2019).

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Community involvement

This project was conceptualized in partnership with the Fort Nelson First Nation Lands Department to evaluate whether recovery expectations along LIS lines were being met. As such, questions and field methods were developed with FNFN, and field data were collected in partnership with FNFN Guardians. One of the co-authors of this paper is the Lands and Resources Coordinator for FNFN.

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Data availability

Data generated or analyzed during this study are available from BC Oil and Gas Research and Innovation Society (BC OGRIS) (https://www.bcogris.ca/projects/natural-recovery-on-low-impact-seismic-lines-in-northeast-bc/). Data are available from the authors upon reasonable request and with permission.

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Competing interests

The authors declare there are no competing interests.

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Appendix A

Fig. A1. Examples of four mulched low-impact (LIS) seisimc lines in forested peatlands in NE BC showing advanced recovery of conifer trees and minimal disutrbance to the substrate and surface mictoropography. Each example is from a black spruce-dominated bog. All photos taken by Jesse Tigner.

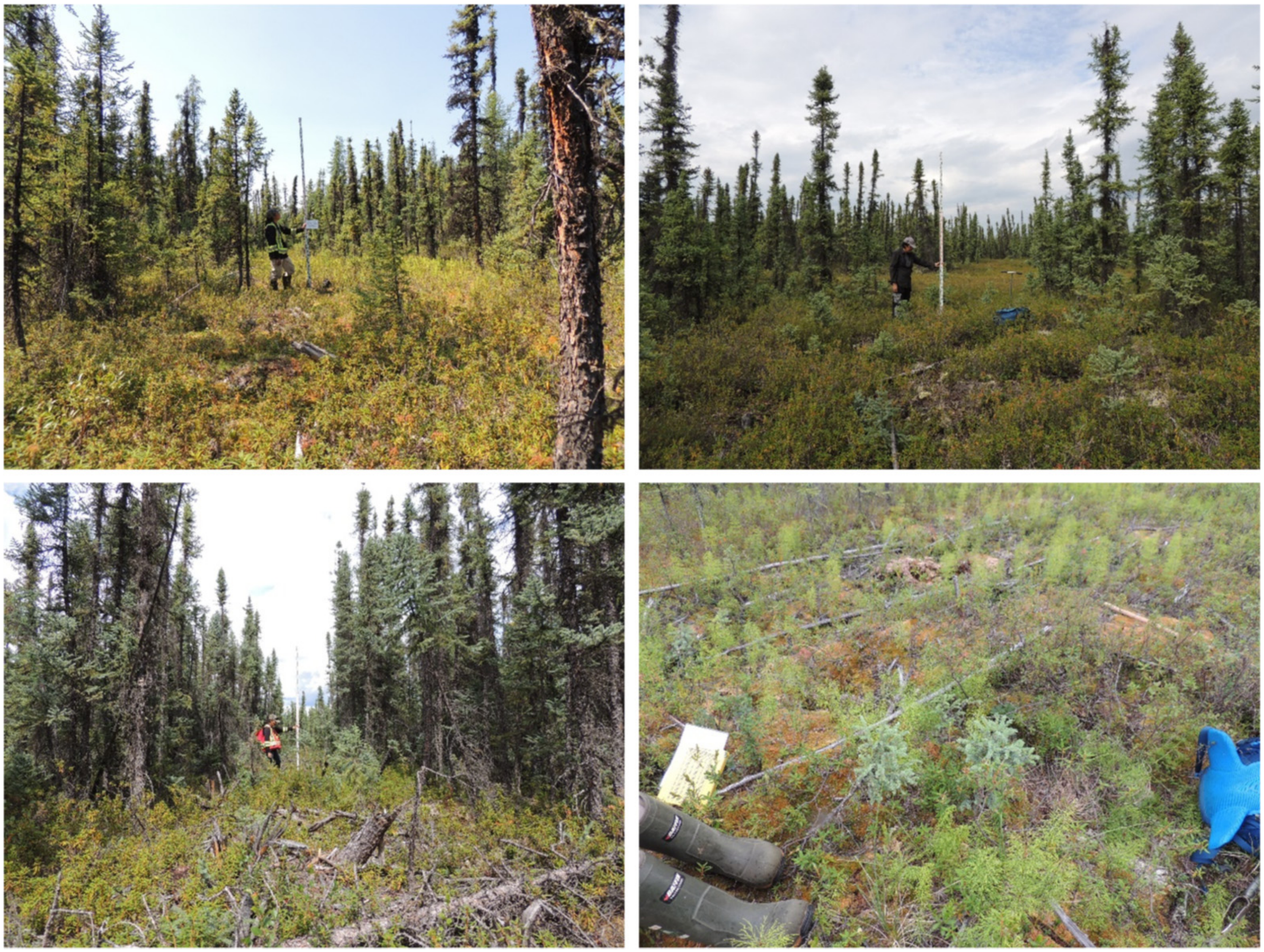

Table A1. Response and predictor variable definitions.

Variable	Definition
Response variables	
Tree occurrence	
Retained tree	Tree older than the line, presence (1) and absence (0)
Recruited tree	Tree younger than the line, presence (1) and absence (0)
Tree density (stems/ha)	
Retained tree	Number of stems classified as retained trees
Recruited tree	Number of stems classified as recruited trees
Tree height (cm)	
Retained tree	Average height of stems classified as retained trees
Recruited tree	Average height of stems classified as recruited trees
Predictor variables	
Proxies for mulching blade height	
Snow depth (cm)	Accumulated precipitation, December to end of February, at the year of line construction
Stump height (cm)	Average height of the remnant mulched tree stems
Line characteristics	
Age (years)	When the seismic lines were cut or time since disturbance
Bearing	Orientation of the line converted to a 0–1 index, north–south (1) and east–west (0)
Continuous mulch	Distribution pattern of deposited mulch, continuous (1), and scattered (0)
Depth to water table (cm)	Distance from the surface to hit 100% saturated substrate
Disturbed substrate (%)	Amount of surface damaged by mulcher blades
Width (m)	The distance across the narrow dimension of the seismic line
Vegetation variables	
Adjacent canopy cover (%)	The amount of sunlight blocked by the trees adjacent to the seismic line
Adjacent stand height (m)	The height of trees adjacent to the seismic line
Shrub density (stems/ha)	All live stems of shrub species (willow, birch, Labrador tea, etc.) $\geq$0.5 m in height

Table A2. Response and predictor variable methods of measurement.

Variable	Measured with
Response variables	
Tree occurrence	
Retained tree	Presence/absence
Recruited tree	Presence/absence
Tree density (stems/ha)	
Retained tree	Count
Recruited tree	Count
Tree height (cm)	
Retained tree	Measuring tape (nearest 0.5 cm)
Recruited tree	Measuring tape (nearest 0.5 cm)
Predictor variables	
Proxies for mulching blade height	
Snow depth (cm)	Averaged from three meteorological stations in the study area
Stump height (cm)	Measuring tape (nearest 1 cm)
Line characteristics	
Age (years)	Data from BC Oil and Gas Commission and seismic shot tags
Bearing	Compass (nearest degree)
Continuous mulch	Presence/absence
Depth to water table (cm)	Digging a hole and measuring tape (maximum 100 cm)
Disturbed substrate (%)	Percent cover
Width (m)	Measuring tape (nearest 1 cm)

Table A2. (*concluded*).

Variable	Measured with
Vegetation variables	
Adjacent canopy cover (%)	Concave densiometer
Adjacent stand height (m)	Clinometer
Shrub density (stems/ha)	Count

Table A3. Response and predictor variable characteristics (occurrence, minimum, median, maximum, mean, and standard error, SE).

Variable	% Occurrence	Minimum	Median	Maximum	Mean (S.E.)
Response variables					
Tree occurrence (%)					
Retained tree	69	–	–	–	–
Recruited tree	64	–	–	–	–
Tree density (stems/ha)					
Retained tree	–	0	1667	32,500	3380 (504)
Recruited tree	–	0	1667	50,833	5965 (963)
Tree height (cm)					
Retained tree	–	3	35	182	42 (1.28)
Recruited tree	–	1	8	140	11 (0.42)
Predictor variables					
Proxies for mulching blade height					
Snow depth (cm)	–	12	25	63	26 (1.40)
Stump height (cm)	–	0	17	47	18 (1.08)
Line characteristics					
Age (years)	–	2	7	11	7 (0.28)
Bearing (north–south orientation)	49	–	–	–	–
Continuous mulch	38	–	–	–	–
Depth to water table (cm)	–	1	58	100	58 (2.93)
Disturbed substrate (%)	48	0	0	75	15 (1.91)
Width (m)	–	1.3	3	6.2	3.1 (0.11)
Vegetation variables					
Adjacent canopy cover (%)	–	0	0	50	7 (1.01)
Adjacent stand height (m)	–	0	6	27	7 (0.33)
Shrub density (stems/ha)	–	0	5	69	9 (1.14)