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Caribou Conservation: Restoring Trees on Seismic Lines in Alberta, Canada

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Received: 22 December 2018; Accepted: 18 February 2019; Published: 20 February 2019

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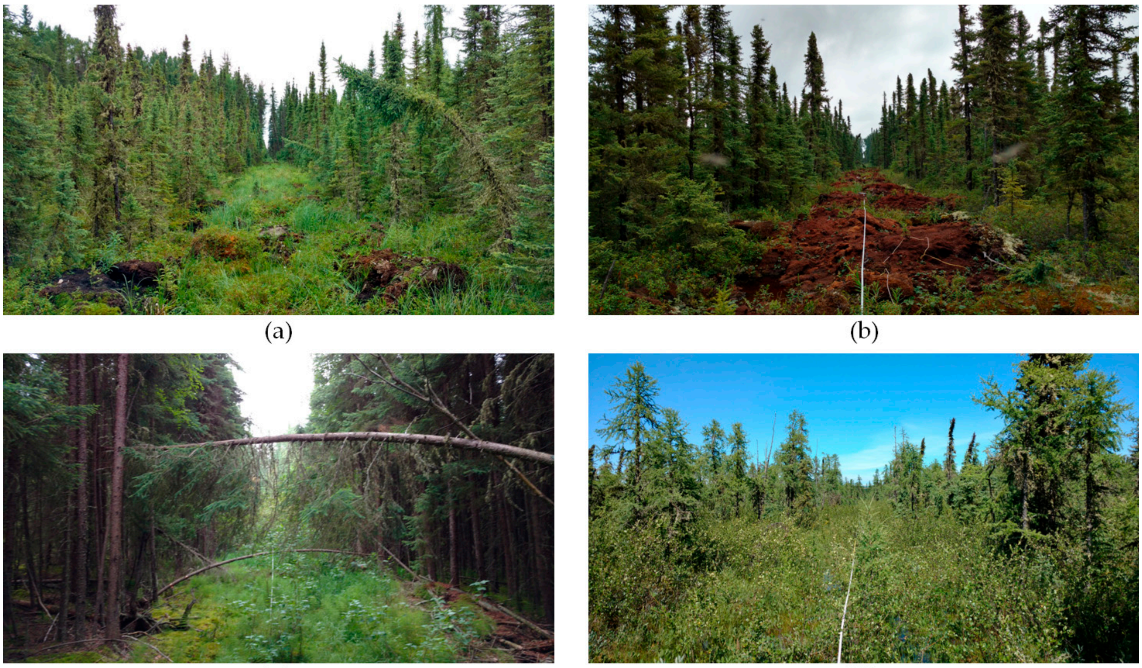
Abstract: Seismic lines are narrow linear (~3–8 m wide) forest clearings that are used for petroleum exploration in Alberta's boreal forest. Many seismic lines have experienced poor tree regeneration since initial disturbance, with most failures occurring in treed peatlands that are used by the threatened woodland caribou (*Rangifer tarandus caribou*). Extensive networks of seismic lines, which often reach densities of 40 km/km^2, are thought to have contributed to declines in caribou. The reforestation of seismic lines is therefore a focus of conservation. Methods to reforest seismic lines are expensive (averaging $12,500 per km) with uncertainty of which seismic lines need which treatments, if any, resulting in inefficiencies in restoration actions. Here, we monitored the effectiveness of treatments on seismic lines as compared to untreated seismic lines and adjacent undisturbed reference stands for treed peatlands in northeast Alberta, Canada. Mechanical site preparation (mounding and ripping) increased tree density when compared to untreated lines, despite averaging 3.8-years since treatment (vs. 22 years since disturbance for untreated). Specifically, treated lines had, on average, 12,290 regenerating tree stems/ha, which is 1.6-times more than untreated lines (7680 stems/ha) and 1.5-times more than the adjacent undisturbed forest (8240 stems/ha). Using only mechanical site preparation, treated seismic lines consistently have more regenerating trees across all four ecosites, although the higher amounts of stems that were observed on treated poor fens are not significant when compared to untreated or adjacent undisturbed reference stands.

Keywords: tamarack; black spruce; seismic line; forest gap; boreal forest; woodland caribou; forest regeneration; silviculture; mechanical site preparation

1. Introduction

The leading anthropogenic contributor of forest disturbances in Alberta is seismic lines [1,2], which reach densities of up to 40 km/km^2. Seismic lines are narrow (3–8 m) linear clear-cut disturbances (Figure 1), which are often in a grid-like network that is created for underground petroleum exploration. These features are called seismic lines due to the use of seismic vibrations that map underground petroleum resources. Research has demonstrated the effects of seismic lines on biodiversity [3,4] and of particular interest in the decline of woodland caribou (*Rangifer tarandus caribou*) [5,6], a species-at-risk in Alberta [7]. These effects are often most pronounced in treed peatlands where forest recovery to disturbance is slow [8,9] and of high conservation value given the local use of these habitats by woodland caribou [10]. Approximately 35% of the world's peatlands are within Canada, covering about 12% (or 1.24 × 10^6 km^2) of the country and up to 50% of northern Alberta [11,12]. In the portions that are treed, slow growing black spruce (*Picea mariana* (Mill.) B.S.P.) and tamarack (*Larix laricina* (Du Roi) K. Koch) tend to dominate, where most other tree species cannot be established. These treed peatlands are the preferred habitat of woodland caribou, allowing them to separate themselves from predators and other prey, since predation is the limiting factor on woodland caribou survival [10]. Seismic lines in treed peatlands alter vegetation composition by promoting early seral shrubs and increasing access into woodland caribou habitat (treed peatlands) that benefit white-tailed deer (*Odocoileus virginianus*) and moose (*Alces alces*) [13]. Increases in deer and moose numbers result in increases in their primary predator, wolves, which, together with greater access into treed peatlands from seismic lines, are thought to lead to greater predation rates on caribou, thus representing a case of apparent competition [14,15].



(a) (b) (c) (d)

Figure 1. Examples of seismic lines in northern Alberta, Canada: (**a**) treated (mounding and planting) poor fen; (**b**) treated (mounding and planting) bog; (**c**) untreated poor mesic forest; and, (**d**) untreated rich fen. All photographs by Angelo T. Filicetti.

The mechanized creation of seismic lines can simplify microtopography, remove peat and soil, and create a depressed surface, all of which lead to failures in tree recruitment [8,9,12,16]. The failure to recruit trees in treed peatlands has resulted in open seismic lines that lack trees for in excess of 50 years. Typically, trees in peatlands grow on hummocks versus hollows as areas with higher depth to water improve the survivability and growth of trees, which is likely due to a larger rooting depth, a warmer microclimate, and better aeration [12,17–19]. Thus, a restoration in microtopography and/or creation of elevated sites may be required for future tree recruitment on seismic lines within treed peatlands.

Restoration treatments of seismic lines in northeast Alberta average $12,500 (CAD) per km. The high costs for treatments on seismic lines are due to their narrow linear shape (kilometers long but only 3–8 m widths) and their remoteness (exceedingly difficult to access). The treatments often involve site preparation (mounding, ripping) and tree planting. Mounding involves the excavation and inversion of organic and mineral soil, resulting in a raised mound of material and an adjacent depression, essentially creating an artificial hummock and hollow [20]. These mounds create an elevated growing site (hummock) for potential seedlings with favourable conditions, thus increasing the potential rooting depth and providing warmer microclimate and better aeration [21,22]. Ripping is applied to drier sites (in this paper, referred to as poor mesic, which typically occurs on small inclines in elevation due to the nature of the undulating plains in this area) and it consists of a plow or ripping teeth that are used to de-compact the soil and create microsites that improve moisture availability and aeration [21,22]. Leave-for-natural passive restoration that waits for natural recovery has no additional costs, but, due to the limited information available on where natural recovery is successful, how long it takes, and the poor rate of recovery that seismic lines in treed peatlands have exhibited, it is uncertain where this type of strategy can be used [8,9].

Delayed recovery of seismic lines, especially in the woodland caribou range, has led to significant efforts to actively restore them. These restoration treatments are currently voluntary, with the possibility of being regulatory in the future. Restoration projects, such as those by Cenovus Energy, Canadian Natural Resources limited (CNRL), and the Regional Industry Caribou Collaboration (RICC), aim to restore seismic lines in woodland caribou habitat by using mechanical site preparation (MSP) to stimulate the survival and growth of seedlings. Since there is limited published literature evaluating the success of these practices in treed peatlands, we evaluated the response of trees (planted and natural ingress) to different restoration treatments that are related to site preparation and tree planting in treed peatlands to better understand how treatments interact with site factors to promote the survival and growth rates of seedlings. Specifically, we hypothesize that the MSPs of lines will increase regeneration rates relative to that of untreated lines and that untreated lines will have lower regeneration rates than the adjacent forest controls, illustrating the conservation issue of a general lack of natural regeneration on seismic lines. Although treatments alone are predicted to facilitate natural regeneration, we measured a number of site factors (stand height, basal area, water availability, line orientation, etc.) to assess and control for their effect on local regeneration patterns.

2. Materials and Methods

2.1. Study Area

We examined seismic line tree regeneration for three restoration projects, which include the Cenovus Energy LiDea 1 and LiDea 2 projects and the CNRL Kirby project, both within the Athabasca Oil Sands of northeastern Alberta between the communities of Conklin and Cold Lake (Figure 2). The three restoration project areas were applied at different times and locations. The seismic lines in these areas were initially cleared in the mid-1980s to the late-1990s, with MSPs being applied to these lines between 2012 and 2015. On average, the untreated seismic lines were last disturbed (cleared) ~22 years prior to field measures, while treated seismic lines had MSP applied ~3.8 years prior to field measurements. Widths of seismic lines ranged from just under 3 m to just over 8 m (see Figure 1 for examples).

Plantings on treated lines reflected tree species that were present in the adjacent control forest that is typical of the ecosite (tamarack in fens, jack pine (*Pinus banksiana* Lamb) in poor mesic, black spruce across all of the ecosites). Tree planting for treated seismic lines was at a rate of ~1,300 stems per hectare. This density was chosen due to uncertainty regarding the amount of natural ingress and the number of viable microsites that would be created by the large mounds, but allowed for a minimum of one planting per mound. Planting was carried out during the last week of July and the first week of August, with summer stock being grown from the Mostoos Hills Central Mixedwood Uplands (CM 3.1) Seedzone following the Alberta Forest Genetic Resource Management and Conservation Standards [23]. All of the seedlings were grown in standard 410A styroblocks; pine seedlings were grown in blocks with copper coating to prune roots.

Mounding was accomplished using a 20 tonne construction excavator with a bucket attachment (sizes were 0.75 to 0.90 m^3). Site preparation was completed by excavating and inverting material, forming a mound of mineral and organic soil and an adjacent depression. Equipment operators were instructed to make mounds that were 0.75 m in width, 1 m in length, and 0.80 m in height, allowing for settling, which was expected to occur with mounded organics. Three mounds were placed across the width of the seismic line, in a diamond or checkered pattern, regardless of the seismic line width. A mound was placed in the middle of the seismic line width every 6 m. Similarly, every 6 m, an additional two mounds were placed along the seismic line length, between the center mounds, at the opposite edges of the seismic line width, creating a 1-2-1-2-1 checkered pattern.

This area lies within the boreal forest zone and it is characterized by a gently undulating plain, where even small changes in microtopography (0.5 m) can result in different moisture regimes and vegetation [24]. The focus of this study is on treed peatlands, which are classified as treed bog, poor fen, rich fen, and poor mesic ecosites using the Alberta Biodiversity Monitoring Institute (ABMI) ecosite classification. Dominant tree species are black spruce, tamarack, and to a lesser extent, jack pine. Wildfires have affected both the LiDea 1 and LiDea 2 sites with fires occurring in 1980 and 1993, respectively, although only affecting a minority of the overall treatment area. In both project areas, the wildfires occurred several years before the seismic lines were created and therefore many years before MSPs.

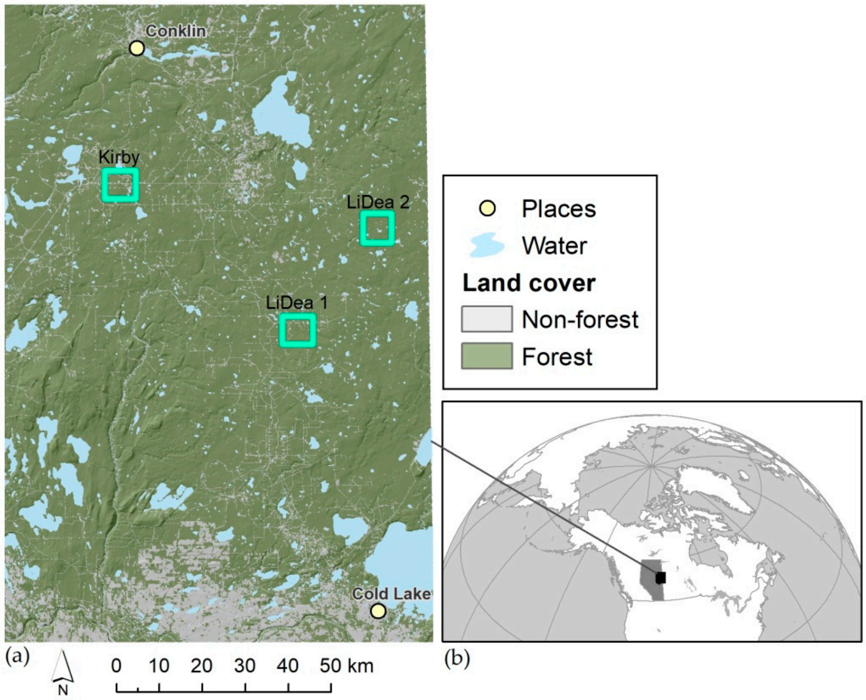


Figure 2. Location of the study areas: (**a**) notable population centers and the location of the three restoration projects (Kirby, LiDea 1, and LiDea 2) within this study; and, (**b**) outline of the province of Alberta, Canada within North America, and location of study.

2.2. *Site selection and field methods*

To avoid pseudo replication, the criteria for selecting sample sites on untreated seismic lines were: (1) minimum distance between plots of 400 m; and, (2) distance may be less between plots only if on a separate seismic line with a different orientation (more than a 45° difference) and/or if ecosite altered within a 400 m radius. Sampling of treated seismic lines was limited to where MSPs were applied, but with use of similar criteria to the untreated lines. The starting locations of plots on seismic lines, once sites were located, were based on a random toss of a metal stake.

Overall, 127 sites with paired plots, with one plot on the seismic line and one plot in the adjacent forest, were sampled in the summer of 2017 for a total of 254 plots. The sampling distribution by ecosite included eight bogs (16 plots), 51 poor fens (102 plots), 33 rich fens (66 plots), and 35 poor mesic sites (70 plots). This distribution of samples reflects the abundance of different ecosites in the area with, for instance, bogs being increasingly uncommon in the project areas.

Each site (paired plots—seismic line and adjacent forest control) was selected based on the requirement of having uniform forest stand conditions (i.e., height, density, age) for the pair of plots, with each plot consisting of a 30 m transect. The seismic line transects were located in the center of the seismic line, while the adjacent paired control plots were located 25 m into the adjacent forest running parallel to the seismic line. A coin toss was used to randomize which side of the seismic line the adjacent forest control plot was located. The tree regeneration and forest stand conditions on the seismic lines and adjacent forest stands were measured along 30 m transects with regenerating trees and shrubs being counted in 1 m × 30 m 'belt' quadrats and trees (≥1 cm diameter at breast height (DBH)) counted in 2 m × 30 m belt quadrats. Additional information was collected in the adjacent forest stand, including stand basal area by species using a two-factor metric prism at the midpoint of the forest transect (15 m), stand age of representative mature trees in the plot using dendrochronology via tree cores, and representative tree height using a hypsometer (Haglof Vertex IV, Langsele, Sweden).

2.3. Regeneration Density by Restoration Area, Restoration Treatment, Plot Location, and Stand Characteristics

Since the creation of the seismic line and the initial application of MSPs destroy/kill all mature trees and well over 90% of regenerating trees, all of the trees on the seismic line can be considered to be regenerating trees. We wanted to have most, if not all, trees on the seismic line being considered to be regenerating trees, as we are interested in how well seismic lines are restoring, but this becomes problematic when comparing to the adjacent forest. We therefore used a "cut-off DBH" to classify regenerating trees for both seismic lines and adjacent forests. Accordingly, a regenerating tree is defined as any tree in the seismic line or adjacent forest less than 1 cm DBH, which accounted for >97% of all trees on seismic lines (see Table 1).

Table 1. Stand characteristics and tree regeneration rates for 127 sites (254 plots) sampled in northeast Alberta, Canada. S.E. is standard error.

Stand Variable	Minimum	Median	Maximum	Mean (S.E.)
Age	5	52	165	56.6 (1.8)
Height	2	9.5	25.2	10.3 (0.3)
Basal area (m^2/ha)	0	12	44	13.7 (0.5)
Tree stems per ha (DBH < 1 cm)				
Seismic line	0	9000	39,333	10,186 (719)
Adjacent stand	0	6000	48,333	8236 (631)
Tree stems per ha (DBH ≥ 1 cm)				
Seismic line	0	0	2500	68 (29)
Adjacent stand	1333	14,333	45,000	14,587 (743)

First, to visualize the main experimental effects, we plotted the mean and standard errors of regeneration density (stems per ha) for all tree species (see Figure A1, Tables A1 and A2 in Appendix A) against the restoration area (LiDea 1, LiDea 2, and Kirby), ecosite, restoration treatment (untreated, mounding/planting, ripping/planting), and plot location (seismic line versus adjacent forest) for all 127 sites (254 plots). Preliminary analyses found that the ecosite was highly influential in the patterns of regeneration density (particularly for certain species) with multiple interactions being required to account for ecosite level complexity. To minimize the complexity of models and to better understand ecosite-specific responses, we analyzed separately regeneration by each ecosite.

Responses were assessed using generalized linear mixed effects models (xtreg command in STATA 15.1/SE; StataCorp, 2017, College Station, TX, USA) [25], where we related linear changes (gaussian distribution, identity link with exchangeable correlation structure) in regeneration density ($\log_{10}$ transformed with a constant of 1 added) to the restoration area (LiDea 1, LiDea 2, or Kirby), restoration treatment (untreated, mounding/planting, or ripping/planting), plot location (seismic line versus adjacent forest), and stand variables (basal area, stand height, and stand age). Site was used as a random effect to account for the paired nature of the seismic line and the adjacent control forest plots. Separate binary dummy variables were used to represent the presence in a project restoration area (0 if site was not in project area and 1 when site was in project area), restoration treatment (0 for untreated as reference category and 1 for treated), and plot location (0 for adjacent forest reference category and

1 for seismic line). The responses on restoration area, therefore, reflect the possible regional differences between areas, while the responses on seismic lines reflect changes from the adjacent forest stand.

Model selection was as follows: (1) main treatment variables (restoration treatments and binary seismic line location variable) were included, regardless of their significance given the purpose of the study; and, (2) variables for site location and stand characteristics were tested and only included if significant (at $\alpha = 0.05$). Collinearity was assessed using Pearson correlations with no variables being considered colinear ($|r| \geq 0.7$, the highest correlation was between stand height and basal area at $r = 0.67$). For the final model, we report model parameters for treatment variables and other significant variables, as well as model goodness of fit using the 'overall' R^2, the 'between' R^2 (representing variance between sites such as fire severity and stand conditions), and the 'within' R^2 (representing variance within sites or in this case the binary seismic line variable) components. Note that these are pseudo-R^2 values and thus they represent relative measures of fit.

2.4. Regeneration Patterns Based on Seismic Line Characteristics

For this analysis, regeneration density was defined as any tree in the seismic line, regardless of its DBH with analyses being restricted only to seismic lines (adjacent forests plots removed resulting in 127 plots), allowing for seismic line characteristics to also be tested. Here, we are assessing the effectiveness of restoration treatments and that of line orientation, line width (forest gap), stand conditions, and ground cover (visual estimates of percent ground cover were assessed along 2 m $\times$ 30 m belt quadrats). As the removal of all adjacent plots eliminates the paired design, we used simple linear regression (reg command in STATA 15.1/SE; StataCorp, 2017, College Station, TX, USA), again using the $\log_{10}$ transformed regeneration density as the response variable. A similar model selection process was used as that in Section 2.3, but without the random effect for plot location, since the pair of plots was not used and here the inclusion of seismic line variables of line orientation, line width (forest gap), and ground cover variables. The line width varied between 2.5 m and 8.5 m (mean of 4.9 and SE (standard error) = 0.1), while line orientation represented the compass bearing of seismic lines that were transformed to an index between 0 (east-west orientation) and 1 (north-south orientation) following the methods of [9]. Most lines in the area were on north-south and east-west axes. Forest stand measures of tree height, stand basal area, and stand age were considered, including their interaction with other factors, such as seismic line (forest gap) width and orientation.

2.5. Tree Regeneration Height on Seismic Lines and Time Since Disturbance

For each seismic line, we also measured the height of regenerating trees within the 1 m $\times$ 30 m belt quadrat to identify which factors promote the growth of trees. Analysis and model selection is identical to Section 2.4 and no significant responses were observed. Similarly, time since disturbance (creation of the seismic line and application of MSP) was never significant in any of the models.

3. Results

3.1. Overall Characteristics

The age of stands ranged from 5 to 165 years (mean of 56.6, SE = 1.8), stand height varied from 2 to 25.2 m (mean of 10.3, SE = 0.3), basal area (using a 2x factor prism) in adjacent stands varied from 0 to 44 m^2/ha (mean of 13.7, SE = 0.5), while trees per hectare ranged from 1333 to 45,000 (mean of 14,587, SE = 742.8). See Table 1 for a list of stand conditions across the plots. The most common tree species, in order of most to least common, were: black spruce, tamarack, jack pine, aspen (*Populus tremuloides* Michx.), Alaska birch (*Betula neoalaskana* Sarg.), and balsam poplar (*Populus balsamifera* L.); similarly, the most common shrubs were: willow (*Salix* spp.), bog birch (*Betula pemula* L.), and prickly rose (*Rosa acicularis* Lindl.).

On average, the treated lines have 12,290 (SE = 890) regenerating stems/ha, untreated lines have 7680 (SE = 1085) regenerating stems/ha, and the adjacent undisturbed forests have 8240 (SE = 631) regenerating stems/ha. Treated lines, therefore, have 1.6-times more regenerating stems per hectare than the untreated lines and 1.5-times more stems per hectare than adjacent undisturbed forests (Figure 3). There are more regenerating stems on treated seismic lines, when compared to untreated lines and adjacent undisturbed forests across each ecosite (Figure 3). For bogs, poor fens, rich fens, and poor mesic sites effect size suggest that the treated seismic lines are, respectively, 85%, 56%, 81%, and 82% more likely to have higher regeneration rates than the average untreated seismic line and that adjacent forests are likely to have 81%, 45%, 60%, and 57% higher regeneration rates than the average untreated seismic line. Note the lack of larger trees (DBH ≥ 1 cm) on seismic lines as compared to adjacent stands, illustrating low tree growth and survival on seismic lines in treed peatlands.

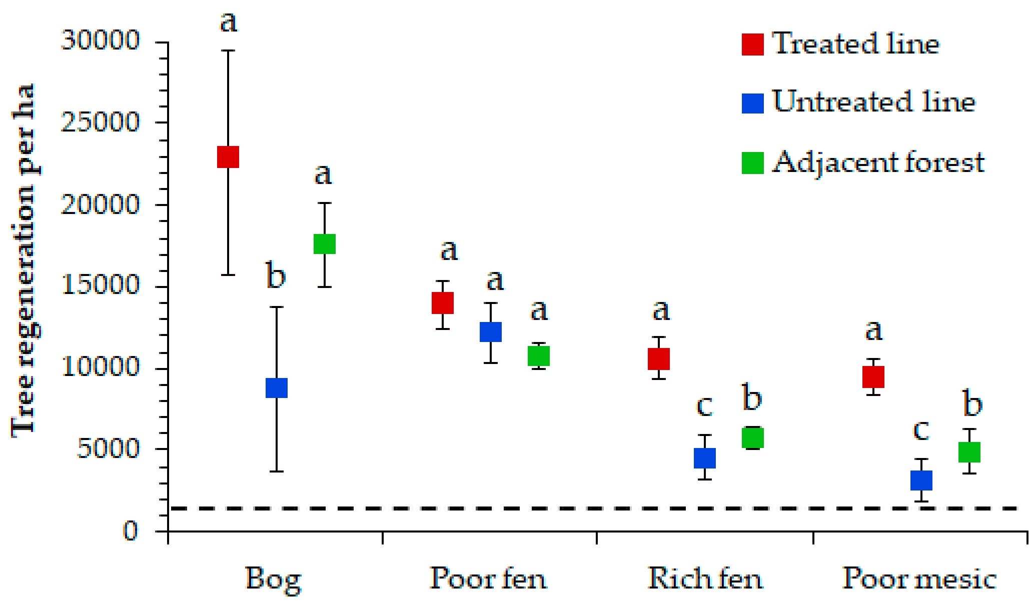


Figure 3. Mean and standard error (error bars) of tree regeneration (diameter at breast height (DBH) < 1 cm), across four ecosites and three treatments. Significance of treatments within each ecosite was tested with a pairwise comparison (Bonferroni adjustment) with different letters indicating significant ($p < 0.017$) differences within an ecosite. Note, dashed line represents the amount of planted stems per hectare in treated lines (1300 stems/ha).

3.2. Restoration Effectiveness on Seismic Lines Versus Adjacent Forest

Untreated seismic lines consistently had lower tree stem density for bog, rich fen, and poor mesic ecosites when compared to adjacent reference forests (see Figure 3 and Table 2), but not for poor fens. Similarly, restoration treatments consistently increased the numbers of tree stems in bogs, rich fens, and poor mesic ecosites, but once again, not for poor fens. Restoration sites also affect tree density with the LiDea 1 site having higher average stem densities in poor fens than the other two restoration areas. Nevertheless, the LiDea 2 site had a lower average stem density in rich fens (Table 2). Note, the time since treatment and time since the creation of the line were never individually significant. Overall model fit was low for poor fens ($R^2 = 0.08$, $p = 0.04$) and moderately high for all other ecosites ($R^2 > 0.30$, $p < 0.01$). Within model fit reflected the strength of the difference between the seismic line and adjacent forest plot, with R^2 being low in both types of fens ($R^2 = 0.04$ for poor fens and $R^2 = 0.17$ for rich fens) and high ($R^2 > 0.50$) for both bogs and poor mesic forests (Table 2).

Table 2. Random effect linear model (xtreg) parameters (coefficient, β; and standard error, SE) relating regeneration density (DBH < 1 cm) (log_{10} transformed) of all tree species to all three restoration areas, restoration treatment (mounding and planting or ripping and planting), and seismic line location (vs. adjacent forest control). Both restoration treatment and seismic line location were included regardless of significance. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Tree Density (stems/ha)	Bog β (SE)	Poor Fen β (SE)	Rich Fen β (SE)	Poor Mesic β (SE)
Constant (intercept)	16,450 (30) ***	7743 (14) ***	6454 (20) ***	2710 (20) ***
Site (restoration area)				
LiDea 1		41 (17) *		
Kirby				
LiDea 2			−44 (24) **	
Restoration treatment				
Mounding & Planting	300 (67) **	34 (24)	271 (37) ***	N/A
Ripping & Planting	N/A	N/A	N/A	731 (38) ***
Seismic line location				
Seismic line plot	−70 (52) **	−16 (20)	−55 (32) **	−63 (30) ***
Model statistics				
n	16	102	66	70
R^2 (within)	0.52	0.04	0.17	0.51
R^2 (between)	0.29	0.12	0.44	0.21
R^2 (overall)	0.41	0.08	0.31	0.32
Wald χ^2	9.82	8.30	27.53	43.72
p-value	0.007	0.040	<0.001	<0.001

3.3. Seismic Line Regeneration Density

When excluding the adjacent forest and including line characteristics and ground cover, the differences in stem density between ecosites were more apparent. Even with the addition of these other factors, the most influential variables were still that of the restoration treatments (see Table 3). The best model describing tree regeneration density on seismic lines in bogs consisted of only the bearing of the seismic line. Here, poor fens, contrary to Section 3.2, significantly benefitted from the restoration treatment, but only when accounting for the abundance of lichen and graminoids, which were detrimental to regeneration. Tree regeneration in rich fens was positively affected by the restoration treatment and stand height, with the mounding and planting treatment being the most effective here when compared to other wet ecosites (bogs and fens). Finally, poor mesic sites benefitted the most of all of the ecosites from their restoration treatment, here being ripping and planting, with no other variable affecting tree regeneration patterns.

Table 3. Linear regression model parameters (coefficient, β; and standard error, SE) relating regeneration density (log_{10} transformed) of all tree species found on seismic lines to restoration treatment, line characteristics, stand variables, and percent ground cover. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. RMSE is root mean squared error.

Tree Density (stems/ha) on Seismic Line Only	Bog β (SE)	Poor Fen β (SE)	Rich Fen β (SE)	Poor Mesic β (SE)
Constant (intercept)	5024 (45) ***	13,012 (22) ***	534 (80) ***	1224 (32) ***
Restoration treatment				
Mounding & Planting		70 (26) *	206 (49) **	N/A
Ripping & Planting	N/A	N/A	N/A	540 (44) ***
Line characteristics				
Bearing	477 (84) *			
Stand variables				
Stand height (m)			19 (8) *	
Ground Cover (%)				
Lichen		−5 (3) *		
Graminoid		−5 (1) ***		

Table 3. *Cont.*

Tree Density (stems/ha) on Seismic Line Only	Bog β (SE)	Poor Fen β (SE)	Rich Fen β (SE)	Poor Mesic β (SE)
Model statistics				
n	8	51	33	35
R^2	0.58	0.30	0.39	0.44
Prob > F	0.028	<0.001	<0.001	<0.001
RMSE	0.36	0.35	0.48	0.46

4. Discussion

4.1. Restoration Effectiveness on Seismic Lines Versus Adjacent Forest

Overall, the results indicate that the presence of a seismic line lowers the tree regeneration rates and that the application of restoration treatments increases the tree regeneration rates across all ecosites (see Table 2). Therefore, early indications suggest that these MSPs are beneficial in initializing the restoration of caribou habitat, thus supporting our initial hypothesis. Except for poor fens, adjacent forests are more likely to have higher regeneration rates than untreated seismic lines, supporting our hypothesis, but the effect sizes suggest only bogs are notable. An untreated seismic line, a clear-cut area (low competition) with a small gap size (easily available seed source), would be expected to have higher regeneration rates than the adjacent forest but this is not being observed in this study or others [8,9]. The lack of tall trees in the untreated seismic lines observed here is similar to other studies [8,9], suggesting that untreated seismic lines in treed peatlands have poor tree growth and survival.

The creation of a seismic line can eliminate microtopography and depress the overall topographic elevation, resulting in shallower water tables and thus changes in ground cover and tree abundance. This includes a general trend towards more tamarack and less black spruce in the untreated poor and rich fens (see Figure A1 and Table A1 in Appendix A). The untreated seismic lines have consistently lower tree densities than adjacent forest controls with poor fens being the exception due to these changes in microtopography and the slow recovery rate and rate of growth in trees in these ecosites. The decades of poor tree density that are experienced on these lines act as pathways of low resistance to wolves and are detrimental in effect to the caribou population. On the other hand, treated seismic lines have consistently greater tree densities than both the untreated seismic lines and adjacent forest controls, with poor fens again being the exception. Furthermore, the treated seismic lines averaged 3.8 years since treatment, while untreated seismic lines were last disturbed (cleared) ~22 years prior. Adjacent forest controls have not been anthropogenically disturbed, although a small number of sampled areas within the restoration projects experienced wildfires in 1980 or 1993. The higher tree densities that were experienced in the relatively short-term (3.8 years) on treated lines can function as obstacles to wolf movement and should benefit caribou populations if the densities stay consistent into the future.

In treated rich fens and, to a lesser degree, poor fens, there is a reversal of the decrease in overall black spruce (see Figure A1 and Table A1 in Appendix A). The lack of black spruce recovery in poor fens seems to account for the deficit in overall tree density experienced post-treatment.

The three restoration areas (LiDea 1, Kirby, and LiDea 2) had minor differences in tree regeneration between them, in fact, there were only two main differences observed. On the one hand, the overall patterns in tree density in LiDea 1 had higher average stem counts in poor fens than when compared to the other two restoration project areas. This suggests that MSP for poor fens in LiDea 1 were perhaps better implemented (differing applications/personnel and/or time since treatment; note, time since treatment and the creation of the line were never significant on their own). Another possibility could be that the LiDea 1 area was, on average, drier or had a higher depth to water than the other two restoration sites. On the other hand, the LiDea 2 site had a lower stem count in rich fens, which may reflect the fact that the restoration area experienced wildfire in 1980, potentially was wetter (trees were shorter and with lower basal area), or had less effective treatments. There were, however, differences when considering individual species (see Figure A1 and Table A1 in Appendix A).

4.2. Seismic Line Regeneration Density

With the exception of bogs, the most consistent predictor for higher tree densities on seismic lines was the restoration treatment. The best model for bog consisted of only the bearing of the seismic line, suggesting that sunlight may be the largest factor influencing regeneration in bogs. However, these results may be misleading for two reasons: (1) bogs had the lowest sample size; and, (2) most bog sites were in LiDea 2, which partially burned during a fire in 1980, many years before initial seismic line creation and decades before MSPs.

The patterns of tree regeneration in poor fens were complex, despite poor fens having the largest sample size. A pattern for poor fens only becomes significant when mounding and planting was combined with lichen and graminoid ground cover suggesting that the effectiveness of treatments is site dependent and at least partially affected by lichen and graminoid cover or the factors that promote their growth. This may have to do with the way that we classified poor fens in the field, or due to the fact that poor fens are ecologically in between rich fens and bogs, as typically rich fens evolve into poor fens and then into bogs [26]. Perhaps their use as an indicator of water availability reflects the importance of lichen and graminoid ground cover [27] and whether the poor fen is more similar to a rich fen or a bog. Although graminoids can be an indicator of wet conditions (rich fen), they also can increase competition with that of seedlings, while lichen mats may produce poor seedbed conditions [28,29]. Many studies demonstrate the effectiveness of herbicides on seedling survival and growth post-MSP, as they eliminate the competing shrubs and graminoids [30,31]. The application of herbicides on seismic lines would be costly, due to their shape and remoteness, especially if reapplications are necessary. If the current mounding application in poor fens continues to show non-significant effects when compared to untreated lines and adjacent forests, perhaps a different MSP or silvicultural treatment should be considered. Note that there have been reports that MSPs can still have an influence on seedling growth for a period of 10 years [32].

Restoration treatment and stand height affected tree regeneration in rich fens. Of all the wetter ecosites (bogs/fens), rich fens benefited the most (proportionally) from mounding and planting. Stand height is likely a proxy of depth to water table [17,33], a proxy for most of the rich fen sites in LiDea 2 (which was discussed in Section 4.1), and it affects seed dispersal and/or seed abundance (the minimum stand height for rich fens was 3.4 m and the mean was 7.9 m, shorter trees tend to be accompanied with lower basal area and generally less fit trees [34]. A large proportion of natural ingress in treated rich fens is, surprisingly, aspen (see Figure A1 and Table A2 in Appendix A). Aspen is typically not a species found in rich fens and they are unlikely to survive long-term, but it does demonstrate the potential for additional species typical of the ecosite to become recruited on exposed mounds.

Poor mesic sites benefitted the most from their restoration treatment of ripping and planting, with no other factor being found to significantly affect tree regeneration patterns. Ripping and planting could have experienced the most benefit here due to improved germination; it is likely that the limiting factor in poor mesic sites is seedbed conditions and seed availability [35].

4.3. Supplemental Information

The lack of responses in tree height and the effect of time since disturbance or treatment were likely due to: (1) all MSPs were applied within five years of field measurements; (2) all of the MSPs were applied within three years of each other; (3) each project area had their MSPs applied at identical times (+/− a month); and, (4) other studies suggest there is little to no difference in the effect of time since disturbance on untreated lines [8,9].

The densities that were observed on treated sites are likely to decrease over time due to competition and self-thinning, yet no evidence of this was observed during field measurements.

Competition and self-thinning seems unlikely to occur in the near future, as tree densities and heights are not exceedingly high. A study on seismic lines, five-years post-fire in a jack pine (*Pinus banksiana*) dominant stand (a shade-intolerant species), had much higher regenerating tree densities and heights, yet showed no signs of competition/self-thinning [36].

Higher stocking rates, herbicides, and fertilizers could improve survival and growth rates, but at much higher financial and possibly ecological cost. Therefore, if this pilot demonstrates that MSPs are successful at obtaining adjacent forest stand densities and restoring caribou habitat, it would be much more cost effective to apply such treatments elsewhere in the future. Many studies already suggest that mechanical site preparation is the most cost effective treatment to apply for seedling survival and growth [21,31,32], but this had not been formally tested for seismic lines.

Logistics is a key challenge for seismic line restoration in northern Alberta due to the remoteness, wetness, narrow linear shape, and the undulating nature of the landscape, which leads to abrupt changes in ecosites along the line. Within a few hundred meters it is not uncommon to have multiple ecosites, ranging from rich fen to poor xeric. This results in restoration challenges, as a seismic line may require several different MSPs. Winter conditions have proved most effective for use of machinery, given the wet nature of the landscape [22]. The excavators that were used here were chosen for their adaptability as well as their ability to create larger mounds. Continuous mounders have the capacity to improve the productivity of mounding, but this machinery produces smaller mounds. Smaller mounds have been found to be less effective, as they do not overcome issues in wetter landscapes (distance to the water table, drainage, etc.), winter frost damage common in high latitudes, and decreases in size occurring from settling and erosion experienced by mounds in the first years post-creation [20]. Although mounding generally costs more than other MSPs, it is needed to avoid establishment/survival issues with a high-water table and it is typically recommended for such sites [21,31]. Ideally, local variation in water table would be first measured, and then MSP planning would proceed, but water table can experience large fluctuations between years and seasons, with estimates of this variation being complicated and costly [37]. If a suitable estimate for water table could be measured and a cut-off depth found where mounding would be less effective, then other MSPs could be considered. Many of the other MSPs (scalping, trenching, mixing, etc.) are considered to be inappropriate for wet sites that are typical of treed peatlands [21]. Often, ripping is used as a standalone or initial treatment to overcome issues of compaction [31] and it has worked well in poor mesic sites in this study.

5. Conclusions

Seismic lines in treed peatlands are not recovering following disturbance, with some staying unforested for many decades [8,9]. Trees that do establish on seismic lines often have difficulty in growth and survival due to simplification in microtopography and a lower water table depth. Restoration treatments increased tree density when compared to the untreated lines, despite averaging 3.8-years since treatment application (vs. untreated lines averaging 22 years). On average, the treated lines have 12,290 regenerating stems/ha, which is 1.6-times more than the untreated lines (7680 stems/ha) and 1.5-times more than the adjacent undisturbed forest (8240 stems/ha), as well as having consistently more tree stems across all ecosites. MSPs on seismic lines show promise in restoring caribou habitat (treed peatlands), but further studies with a longer time horizon are required. The lack of strong treatment effects between treated and untreated seismic lines in poor fens (the highest sampled ecosite) suggest that the cost-effectiveness of these applied methods are questionable for this one ecosite. Poor and rich fens, though, do experience a shift to higher tamarack density post-seismic line creation and a shift back to more black spruce after receiving mounding treatment. Therefore, mounding can be considered to be an effective restoration treatment for poor and rich fens.

Author Contributions: A.T.F., M.C., and S.E.N. conceived and designed the experiments; A.T.F. collected the data; A.T.F. and S.E.N. analyzed the data; A.T.F., M.C., and S.E.N. wrote the paper.

Funding: This research is part of the Boreal Ecosystem Recovery and Assessment (BERA) project (www.bera-project.org), and was supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) Collaborative Research and Development Grant (CRDPJ 469943-14) in conjunction with Alberta-Pacific Forest Industries, Cenovus Energy, ConocoPhillips Canada and Devon Canada Corporation. Additional funding provided by Northern Scientific Training Program (NSTP) and the Alberta Conservation Association through the ACA Grants in Biodiversity Program.

Acknowledgments: We would like to thank Cassondra J. Stevenson for field assistance throughout this project.

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Appendix A

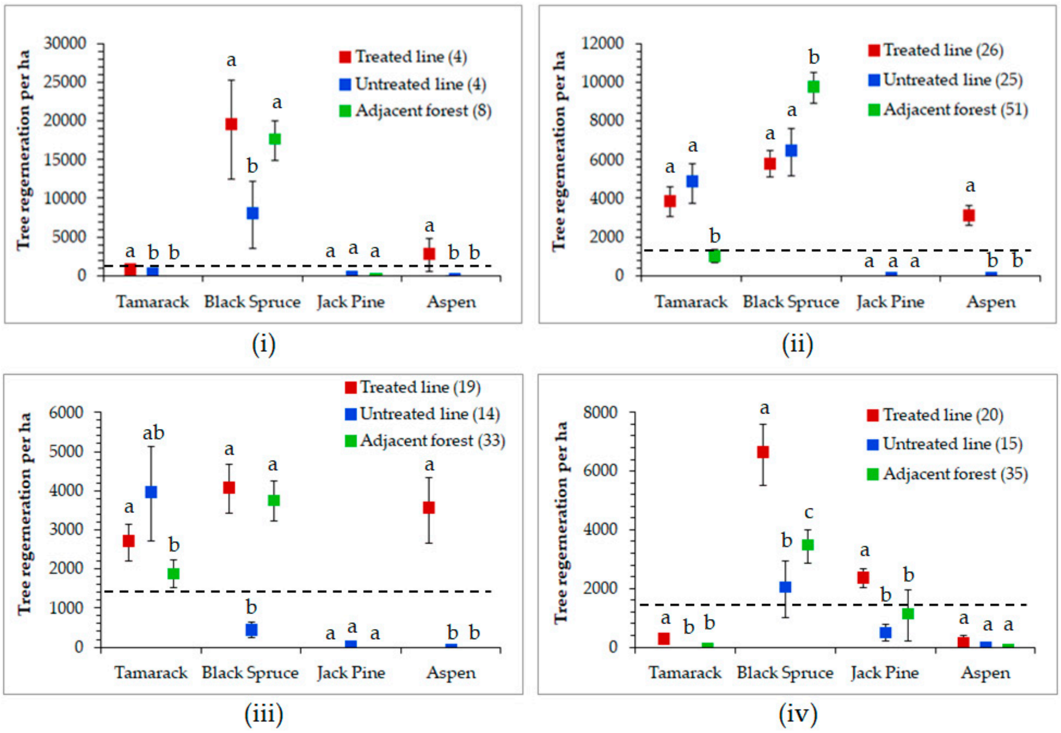


Figure A1. Mean and standard error (error bars) of tree regeneration (DBH < 1 cm), across four tree species and three treatments. Where each ecosite is represented by: (**i**) bog; (**ii**) poor fen; (**iii**) rich fen; and (**iv**) poor mesic. Significance of treatments within each ecosite was tested with a pairwise comparison (Bonferroni adjustment) with different letters indicating significant ($p < 0.017$) differences within a species. Note, dashed line represents the amount of planted stems per hectare in treated lines (1300 stems/ha). Scales vary.

Table A1. Random effect linear model (xtreg) parameters (coefficient, β; and standard error, SE) relating regeneration density (DBH < 1 cm) ($\log_{10}$ transformed) of all tree species to all three restoration areas, restoration treatment (mounding & planting or ripping & planting), and seismic line location (vs. adjacent forest control). Both restoration treatment and seismic line location were included regardless of significance. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Tree Density (stem/ha)	Bog				Poor Fen			
	Tamarack β (SE)	**Black Spruce β (SE)**	**Jack Pine β (SE)**	**Aspen β (SE)**	**Tamarack β (SE)**	**Black Spruce β (SE)**	**Jack Pine β (SE)**	**Aspen β (SE)**
Constant (intercept)	0 (40)	16404 (29) ***		0 (29)	169 (31) ***	7937 (12) ***	3 (5)	4 (11)
Site (restoration area)								
LiDea 1					175 (40) **			
Kirby								
LiDea 2								
Restoration treatment variables								
Mounding & Planting	185 (96)	247 (64) *		836 (67) ***	−9 (48)	26 (25)	−12 (10)	1515 (22) ***
Ripping & Planting	N/A	N/A		N/A	N/A	N/A	N/A	N/A
Seismic line location variable								
Seismic line plot	105 (79)	−71 (51) *		44 (56)	300 (36) ***	−51 (21) ***	10 (9)	19 (18)
Stand variables								
Stand height (m)					−11 (5) *			
Basal area of target tree								
Basal area of other tree species								
Model statistics								
n	16	16		16	102	102	102	102
R^2 (within)	0.55	0.54		0.80	0.39	0.24	0.01	0.85
R^2 (between)	0.16	0.27		0.59	0.20	0.02	0.04	0.60
R^2 (overall)	0.41	0.41		0.73	0.28	0.13	0.02	0.76
Wald χ^2	9.18	9.98		35.42	43.30	16.16	1.97	347.80
p-value	0.010	0.007		<0.001	<0.001	<0.001	0.373	<0.001

Table A1. *Cont.*

Tree Density (stem/ha)	Rich Fen				Poor Mesic			
	Tamarack β (SE)	**Black Spruce β (SE)**	**Jack Pine β (SE)**	**Aspen β (SE)**	**Tamarack β (SE)**	**Black Spruce β (SE)**	**Jack Pine β (SE)**	**Aspen β (SE)**
Constant (intercept)	1974 (33) ***	1263 (22) ***	0 (5)	49 (20) *	13 (13)	8588 (82) ***	185 (30) ***	13 (14)
Site (restoration area)								
LiDea 1	198 (41) **							
Kirby								
LiDea 2				−56 (24) ***				
Restoration treatment variables								
Mounding & Planting	127 (53)	671 (35) ***	−16 (11)	1072 (36) ***	N/A	N/A	N/A	N/A
Ripping & Planting	N/A	N/A	N/A	N/A	150 (27) ***	438 (43) ***	1837 (35) ***	−2 (29)
Seismic line location variable								
Seismic line plot	17 (45)	−87 (30) ***	19 (10)	19 (32)	−16 (23)	−60 (35) **	−9 (27)	17 (26)
Stand variables								
Stand height (m)						−8 (4) *		
Basal area of target tree		9 (2) ***			44 (16) *			67 (14) ***
Basal area of other tree species	−12 (2) ***						−5 (2) **	
Model statistics								
n	33	33	33	33	35	35	35	35
R^2 (within)	0.23	0.55	0.07	0.70	0.35	0.23	0.86	0.02
R^2 (between)	0.51	0.76	0.04	0.68	0.22	0.35	0.24	0.33
R^2 (overall)	0.38	0.67	0.06	0.69	0.28	0.30	0.57	0.19
Wald χ^2	36.72	126.82	3.82	140.05	26.07	26.33	198.10	15.48
p-value	<0.001	<0.001	0.150	<0.001	<0.001	<0.001	<0.001	0.001

Table A2. Linear regression model parameters (coefficient, β; and standard error, SE) relating regeneration density ($\log_{10}$ transformed) of all tree species found on seismic lines to restoration treatment, line characteristics, stand variables, and percent ground cover. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. RMSE is root mean squared error.

Tree Density (stem/ha) on Seismic Line Only	**Bog**				**Poor fen**			
	Tamarack β (SE)	**Black Spruce β (SE)**	**Jack Pine β (SE)**	**Aspen β (SE)**	**Tamarack β (SE)**	**Black Spruce β (SE)**	**Jack Pine β (SE)**	**Aspen β (SE)**
Constant (intercept)	34 (30)	4809 (44) ***		44 (71)	1342 (100) ***	5213 (27) ***	−3 (7)	25 (22)
Site (restoration area)								
LiDea 1					540 (45) ***			
LiDea 2								
Restoration treatment variables								
Mounding & Planting				836 (114) *				1490 (32) ***
Ripping & Planting	N/A	N/A		N/A	N/A	N/A	N/A	N/A
Line characteristics								
Bearing	1152 (53) **	389 (82) *						
Stand variables								
Stand height (m)					−16 (5) **			
Basal area of target tree						4 (2) *		
Basal area of other tree species								
Ground Cover (%)								
Open water						−2 (1) *		
Bryophyte					2 (1) *			
Sphagnum fuscum							2 (1) *	
Graminoid						−3 (1) *		
Model statistics								
n	8	8		8	51	51	51	51
R^2	0.85	0.54		0.59	0.44	0.31	0.10	0.67
Prob > F	>0.001	0.038		0.026	<0.001	<0.001	0.021	<0.001
RMSE	0.25	0.36		0.47	0.54	0.33	0.19	0.43

Table A2. *Cont.*

Tree Density (stem/ha) on Seismic Line Only	Rich Fen				Poor Mesic			
	Tamarack β (SE)	**Black Spruce β (SE)**	**Jack Pine β (SE)**	**Aspen β (SE)**	**Tamarack β (SE)**	**Black Spruce β (SE)**	**Jack Pine β (SE)**	**Aspen β (SE)**
Constant (intercept)	404 (94) *	163 (30) **	8 (8)	186 (44) **	0 (22)	798 (33) ***	256 (29) ***	322 (93) **
Site (restoration area)								
LiDea 1								
LiDea 2				−81 (47) ***				
Restoration treatment variables								
Mounding & Planting		1170 (41) ***		933 (48) ***	N/A	N/A	N/A	N/A
Ripping & Planting	N/A	N/A	N/A	N/A	152 (30) **	450 (46) ***	1265 (36) ***	
Line characteristics								
Bearing								−48 (33) *
Stand variables								
Stand height (m)	18 (8) *							
Basal area of target tree								
Basal area of other tree species							−6 (2) ***	
Ground Cover (%)								
Open water								
Bryophyte								
Sphagnum fuscum								
Graminoid								
Model statistics								
n	33	33	33	33	35	35	35	35
R^2	0.12	0.64	0.00	0.68	0.27	0.38	0.70	0.14
Prob > F	0.047	<0.001	0.000	<0.001	0.001	<0.001	<0.001	0.029
RMSE	0.54	0.42	0.18	0.48	0.34	0.48	0.37	0.35

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