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Natural regeneration of forest vegetation on legacy seismic lines in boreal habitats in Alberta's oil sands region

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ABSTRACT

Mapping of oil reserves involves the use of seismic lines (linear disturbances) to determine both their location and extent. Conventional clearing techniques for seismic assessment have left a legacy of linear disturbances that cause habitat fragmentation. Little is known, however, about how local and landscape factors affect natural regeneration patterns of trees and shrubs on seismic lines that facilitate mapping and future projections of regeneration patterns. To understand factors affecting early forest regeneration and to predict future trends in regeneration of legacy seismic lines we used LiDAR, forest stand databases and a disturbance inventory of conventional seismic lines to model seismic line regeneration to a 3 m height in a 1806 km^2 area in northeastern Alberta, Canada. Regeneration to 3 m was inversely related to terrain wetness, line width, proximity to roads (as a proxy for human use of lines), and the lowland ecosites. Overall, terrain wetness and the presence of fen ecosites had the strongest negative effect on regeneration patterns; the wettest sites failed to recover even after 50 years post-disturbance. Predictions of future regeneration rates on existing lines suggested that approximately one-third of existing linear disturbance footprints in this boreal landscape will remain un-regenerated 50 years later resulting in persistent habitat fragmentation. Model predictions estimating regeneration probability are particularly valuable for estimating current and future forest regeneration trajectories on linear disturbances which are a conservation concern and a focus for restoration and planning by government, industry and conservation organizations.

1. Introduction

The Lower Athabasca region, located in northeastern Alberta, has experienced extensive oil sands development in the past 50 years, having been relatively unaffected by anthropogenic disturbances previously. Exploration of oil sands deposits is done through a seismic assessment (Alberta Energy, 2014), which uses seismic sound waves to map underground oil reserves. To facilitate a seismic assessment, linear corridors commonly referred to as 'seismic lines' are cleared through the forest resulting in habitat fragmentation. Though recent technologies and best management practices since the mid-1990s have substantially reduced the width of seismic lines (Schmidt, 2004; AECOM, 2009), there is an extensive footprint of conventional seismic lines often referred to as legacy seismic lines (Lee and Boutin, 2006). Given the scale and extent of oil sands exploration in the region, seismic lines are considered one of the largest contributors to forest fragmentation in the region with densities as high as 10 km/km^2 (Lee and Boutin, 2006). The high density of seismic lines in the region, together with concern for the condition of boreal species, especially woodland caribou (James and Stuart-Smith, 2000; Dyer et al., 2002; Schneider et al., 2010), has drawn attention to the importance of restoration of these landscape features.

Fragmentation of the boreal forest in Alberta has been shown to affect the behaviour of a number of wildlife species including ovenbirds (Bayne et al., 2005; Machtans, 2006; Lankau et al., 2013), marten (Bayne et al., 2011; Tigner, 2012), black bear (Tigner et al., 2014) and woodland caribou (James and Stuart-Smith, 2000; Dyer et al., 2002). The decline of woodland caribou has been most contentious, with the Federal government responding through a caribou recovery strategy that requires 65% of woodland caribou habitat to be undisturbed by being at least 500 m from any anthropogenic disturbance (Environment Canada, 2012). Seismic lines often represent the largest single footprint when using this definition. Together with habitat conservation and predator

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management, regeneration of seismic lines is considered a necessary step towards sustaining Alberta's threatened woodland caribou herds (Schneider et al., 2010). In Alberta, the 65% disturbance threshold for caribou was surpassed in 1992 with no undisturbed habitat projected to be left by 2028 (Komers and Stanojevic, 2013). Understanding the factors that promote or inhibit seismic line forest regeneration is therefore critical for determining future thresholds (federal targets) for caribou habitat and more generally reducing habitat fragmentation. Open linear corridors in the boreal forest promote the intrusion of people, especially on all-terrain-vehicles, and with this transfer of invasive species (e.g. exotic earthworms), affecting the native biota and disrupting regeneration processes (Cameron et al., 2007; Sanderson et al., 2012).

The linear nature of seismic line disturbances creates a unique condition for regeneration of woody vegetation. Lines are prone to soil compaction, re-use by all-terrain-vehicles (ATVs) and changes in soil temperature and light levels, which lead to lower rates of tree growth (Revel et al., 1984; Lee and Boutin, 2006). Regeneration patterns on a line are influenced by a complex set of factors including disturbance history, stand type, line characteristics (size and orientation), terrain features and human activity. Historically, bulldozers used to clear seismic lines leveled the microtopography resulting in persistent changes to the vegetation (Lee and Boutin, 2006; Caners and Lieffers, 2014). This depressed microtopography is particularly troublesome in fens, where seasonal flooding suppresses the development of hummock-forming *Sphagnum* mosses, allowing sedge-dominated fens to persist without development of woody vegetation (Caners and Lieffers, 2014). Flooding slows growth due to reduced soil temperatures that limit soil aeration and chemical and biological reactions (Lieffers and Rothwell, 1986; Bonan and Shugart, 1989; Levine et al., 1993). Depending on soil moisture and soil frost conditions during disturbance, bulldozers have the potential to compact soil that leads to loss in soil aeration and root penetration (Startsev and McNabb, 2009).

As seismic lines are cleared through a wide range of landforms, there is wide variation in nutrient and moisture regimes along their length (Hiltz et al., 2012). Thus ecosite, a unique combination of moisture and nutrient conditions, and the type of woody and herbaceous species, vary along a line (Revel et al., 1984; Beckingham and Archibald, 1996). As seismic lines dissect forest stands, light availability is affected by its width and orientation (Revel et al., 1984), which affects vegetation composition and speed of regeneration. For example, shade intolerant trembling aspen (*Populus tremuloides* Michx.), quickly establishes after a disturbance if given plenty of light, while black spruce (*Picea mariana* (Mill.) B.S.P), which can withstand cold soils (Bonan and Shugart, 1989), is able to slowly regenerate in shaded sites.

One challenge to assessing recovery patterns on seismic lines is the remoteness, time and cost of field research. Access during the summer months via wheeled vehicles is limited in the area, because of the abundant peatland complexes (fens and bogs). Obtaining adequate field samples at the scale of landscapes and across the diversity of site conditions is challenging and expensive, necessitating in some cases helicopter travel. High resolution remote sensing provides an alternate platform for assessing recovery patterns. The Government of Alberta has acquired Light Detection and Ranging (LiDAR) data over much of the forest zone of Alberta. LiDAR is an optical remote sensing technique that samples the earth's surface in order to provide detailed 3-D depictions of surface topography (x, y, z coordinate measurements) that can characterize vegetation structure (Lefsky et al., 2002). These remote sensing data have been used to develop Wet Areas Mapping (WAM) products that are based on a series of algorithms that predict the cartographic depth-to-water (DTW) and flow accumulation (Hiltz et al., 2012; White et al., 2012). LiDAR data is also helpful in quantifying structural patterns of vegetation, in both vertical and horizontal dimensions (Bollandås et al., 2008; Vierling et al., 2008; Wulder et al., 2012). For example, LiDAR has been used to characterize the horizontal and vertical structure of the forest canopy (Kane et al., 2013) and measures of forest canopy height and gap closure (Vepakomma et al., 2011). LiDAR has also been used to study behavioural responses of wildlife to linear disturbances by ovenbirds and marten (Bayne et al., 2011). Although LiDAR has been widely used for measuring forest attributes, to our knowledge the landscape patterns of vegetation regeneration on seismic lines has not been examined using LiDAR and derived products such as Wet Areas Mapping data.

Due to a lack of understanding of regeneration processes on seismic lines, spatially-explicit projections for restoration planning and management actions are not currently possible. Use of remote sensing and existing spatial (GIS) data to explore recovery patterns could provide insight into regeneration processes and facilitate the mapping of regeneration patterns and projections of recovery. The objectives of this paper are: (1) use LiDAR-derived data, forest stand inventories and a lineal inventory of disturbances (Lineal Characterization Manual and Specifications, 2012) to model local vegetation regeneration on seismic lines in order to better understand the factors affecting patterns in recovery; and (2) use these relationships to predict future landscape patterns of regeneration in northeast Alberta (see Fig. 1).

2. Methods

2.1. Study site

The study area consists of 1806 km^2 of boreal forest south of Fort McMurray within the Stoney Mountain area of northeast Alberta (56° 27′ 37″ N, 111° 42′ 14″ W, Fig. 2). The Stoney Mountain area has a gradual shift in elevation from 246 m in the north to 632 m in the southeast (Fig. 2). The area is primarily within the Central Mixedwood Natural Subregion with a smaller portion of higher elevations in the southeast being in the Lower Boreal Highlands Natural Subregion (Alberta Environment and Sustainable Resource Development, 2005). Vegetation includes black spruce (*Picea mariana*) or tamarack (*Larix laricina* (Du Roi) K. Koch) dominated bogs, poor fens, rich fens and marshes in the lowlands where the soil is saturated for all or part of the year (Beckingham and Archibald, 1996). On upland sites, soils are well drained and dominated by aspen, poplar (*Populus balsamifera* L.), jack pine (*Pinus banksiana* Lamb.), white spruce (*Picea glauca* (Moench) Voss) or

Fig. 1. Ground photograph illustrating typical conventional seismic line disturbance for a wet (j) ecosite in the boreal forests of northeast Alberta, Canada (56° 29′ 35″ N, 111° 18′ 26″ W).

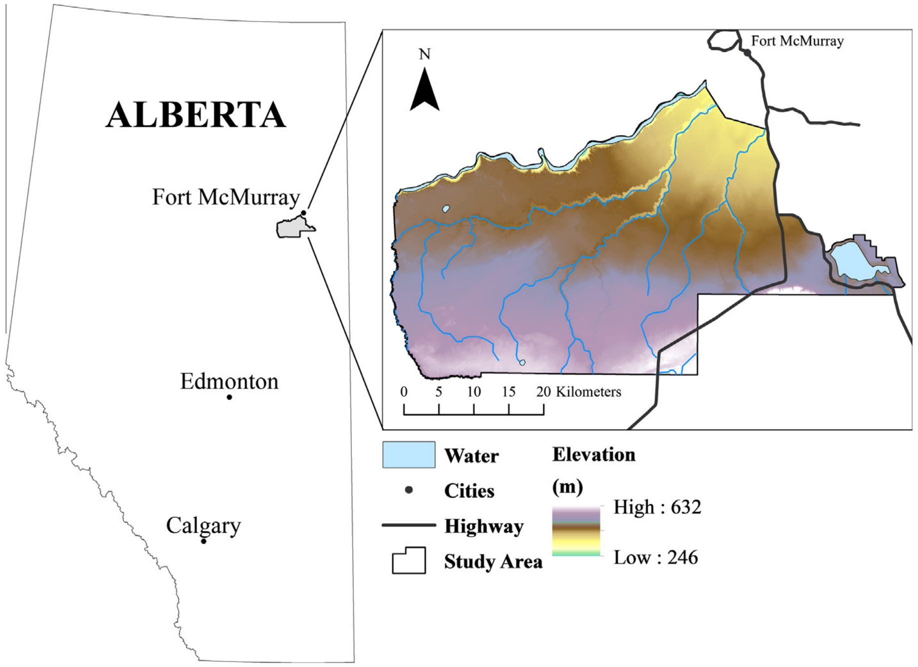

Fig. 2. Planning region map of Stoney Mountain Area in Alberta, Canada (56° 27′ 37″ N, 111° 42′ 14″ W).

balsam fir (*Abies balsamea* (L.) Mill; Beckingham and Archibald, 1996). Mean monthly temperature is −18 °C in January and 15 °C in July with mean annual precipitation being 478 mm (Natural Regions Subcommittee, 2006). July is the wettest month and February the driest (Natural Regions Subcommittee, 2006). The study area is occupied by woodland caribou (Schneider et al., 2010). The Stoney Mountain area has ∼12,000 km of linear disturbances, 4350 km of which are in our study area and 1448 km which are conventional seismic lines (Nash, 2012). Using the caribou recovery strategy of 500 m buffers (Environment Canada, 2012), conventional seismic lines in the study area represent 54.3% of the area being ‘disturbed’.

2.2. Defining of vegetation height on seismic lines

Discrete-return airborne LiDAR (hereafter LiDAR) was captured and calibrated by Airborne Imaging at 1400 m altitude at a flight speed of 160 knots during a leaf-on period in 2007. LiDAR provided a point cloud dataset that depicts ground and above-ground objects. These data were cleaned and prepared using the software TerraScan and TerraModel with a minimum intensity of 1.4 points per square metre and classified into bare-earth (ground) and vegetation (above-ground) points. A minimum vertical accuracy of <30 cm and horizontal accuracy of <45 cm Root Mean Square Error were achieved, which is the square root of the average of the set of squared differences between elevation values from an independent source of higher accuracy. To estimate canopy height we developed a digital elevation model (DEM) using linear interpolation from last return (bare-earth) points contained in a LAS Dataset (LiDAR point cloud) in ArcGIS (v. 10.1). This represented the lowest points, or ground surface. A digital surface model (DSM), which included maximum vegetation heights, was then developed for the study area from first return (maximum height) points. Canopy height was estimated as the difference between these two models (e.g. Canopy height = DSM − DEM). We estimated canopy (vegetation) height for the study area at a 2 m horizontal resolution (i.e. 2 m pixel size) using the LiDAR point cloud. We found that a 2 m horizontal resolution reduced error in height from a 1 m horizontal resolution, eliminating negative height values in cells with too few points, and was still at a small enough resolution to examine vegetation heights specific to conventional seismic lines.

Linear features (i.e. linear footprint) were delineated from an inventory conducted in 2011 by use of aerial photographic interpretation using a 3-dimensional software package called “Softcopy” (Lineal Characterization Manual and Specifications, 2012). All linear features that were longer than 50 m were delineated as polylines and this included roads, pipelines and seismic lines. Polylines representing seismic lines were terminated when they intersected a pipeline, well site or road. Along conventional seismic lines we established 1043 random plots that were 2 × 50 m in size and at least 250 m apart (ArcGIS Create Random Points tool, v10.1) to ensure that they were sufficiently spaced into different ecosites or local terrain conditions. The point cloud data showed a detailed and accurate depiction of the textual surface of the landscape at the time the LiDAR was captured. Due to inaccuracies of the other GIS layers, there were spatial misalignments with the GIS vector layers depicting seismic line location and lineal attribute information during digitization with the LiDAR-derived data (see for example, Bayne et al., 2011). For this reason, each plot was manually adjusted in ArcGIS to be oriented within the approximate centre of the seismic line (parallel to line) as defined by LiDAR-derived data. Only lines greater than 3 m in width were used in the analysis to reduce false signals from adjacent forest stands for a final sample size of 863 plots. Limiting the analysis to lines >3 m wide reduces the chance that the adjacent canopy could have ingressed and closed the gap visible in aerial photography, which could be a concern in aspen stands. Exploration through seismic assessments in the area first started in the 1960s and it is highly improbable that line regeneration exactly resembled the adjacent stand conditions in height, composition and density today, thus reducing likelihood of missing lines. Canopy height and explanatory continuous variables were averaged across the 2 × 50 m plots. The plot therefore reflects the average maximum vegetation height for each 2 m pixel averaged across 25 pixels.

2.3. Explanatory variables used to explain and predict height of vegetation

We used a suite of environmental and disturbance history variables to explain patterns of vegetation height on seismic lines (Table 1). Disturbance history variables included time since clearing of the seismic line (Table 1). To describe the most recent clearing, time since disturbance was estimated at a decadal resolution (i.e. 1970s, 1980s, 1990s, and 2000s) (Lineal Characterization Manual and Specifications, 2012). Tree samples were collected from a subsample of regenerating seismic lines and aged using tree ring analysis to increase confidence in time since disturbance estimates, as industry data was not available for exact years of line clearing and re-clearing. Linear regression results from tree ring analysis indicated good consistency with year of disturbance estimates ($r = 0.76$, df = 114, $P < 0.001$) illustrating accuracy of estimates.

Explanatory variables describing stand characteristics adjacent to the seismic line included ecosite and stand age derived from the Alberta Vegetation Inventory (AVI), which are from interpretations of 1:20,000 scale aerial photos with a sample of field measurements for validation (Alberta Vegetation Interpretation Standards, 2005). Ecosites describe areas with unique recurring combinations of vegetation and soil based on the local moisture and nutrient regime (Beckingham and Archibald, 1996). Ecosites were used as categorical variables and sometimes grouped into similar categories due to low sample sizes and representing here the categories of: uplands (d; reference, modal category); poor (c, g); mesic and nutrient rich (e, f, h); bog (i); fen (j); and wet (k, l) ecosites. The use of a categorical variable in the analysis requires a reference category to compare with other ecosite groups.

Line characteristics included line width and orientation of line. Line widths in the analysis ranged from 4 to 12 m wide. Line orientation was calculated on ArcGIS (v. 10.1) for each polyline segment. We modified the Beers equation (Beers et al., 1966) to re-scale line orientation between zero (east–west axis) and one (north–south axis) using the following equation: Line Orientation=$|(\cos(\theta \times 0.017453)|$, where "$\theta$" is the azimuth in degrees multiplied by a constant to convert to radians and the absolute value of the cosine to 'fold' the function so that east–west and north–south orientations were the same.

Use of lines by ATV's and trucks were considered more likely for locations close to major roads since they would be more accessible. Our human activity index was therefore based on the distance (km) of the plot to the nearest road (primary and secondary) measured on a log10 scale with a constant of 1 added. We hypothesized an interaction between depth-to-water and distance to the nearest road because it is more likely that use of lines occurred at further distances in summer for dry, upland sites than seismic lines that are wet.

Terrain variables included topographic depth-to-water (DTW) and slope. Wet Areas Mapping (WAM) data (1 m resolution) provided by Alberta Environment and Sustainable Resource Development (White et al., 2012) were used to predict depth-to-water. Slope was calculated for the site using ArcGIS (v. 10.1) from a LiDAR-derived DEM at a 1 m resolution. Depth-to-water and slope were averaged across the 2 × 50 m seismic line plot.

2.4. Model selection and analysis

We applied a 3 m rule of vegetation height to define the threshold for initial forest regeneration of seismic lines using the minimum green-up rule required by forestry regulations for wildlife in Alberta (Forest Practices Code, 2001; Alberta Environment and Sustainable Resource Development, 2012). When vegetation has reached an average of 3 m height, it is more likely to be on a trajectory towards structural regeneration as this height is more representative of trees than shrubs. Models explaining seismic line vegetation regeneration to a 3 m height over the 2 × 50 m plot (response variable) were developed from five different *a priori* candidate themes of variables (Table 2). Individual themes represented similar factors that were hypothesized to affect forest recovery on seismic lines. This included characteristics of stand and disturbance history, terrain, and indirect measures of light and moisture. Time since disturbance (AGE) was added to all models because it should be a major predictor of vegetation growth. An interaction between depth-to-water and time since disturbance was hypothesized because the effect of time since disturbance on regeneration is likely dependent on the soil wetness in the plot. Additionally, an interaction with distance to roads and depth-to-water was hypothesized to describe human re-use of lines (less human re-use of lines near roads when wet). An interaction between both time since disturbance and distance to roads, with ecosite was also explored, but this dramatically increased model complexity and thus, interactions with terrain wetness were deemed sufficient. It is important to note that models reflect

Table 1

Explanatory variables used in generalized linear models (GLMs) with a logit link describing probability of seismic line recovery to a 3 m vegetation height. Terrain slope was removed due to collinearity with depth-to-water ($r^2 = 0.6$).

Variable	Abbr.	Type	Prediction	Source
A. Site and disturbance history				
Time since disturbance	Age	Continuous	Positive linear; probability of recovery increases with time	Lineal inventory
B. Line attributes				
Line width	Lwid	Continuous	Negative linear; wider lines increase disturbance severity	Lineal inventory
Line orientation	Azim	Continuous	Negative linear; increased light on NS lines	Lineal inventory
C. Stand characteristics				
Stand age	Stand age	Continuous	Older stands have fewer disturbance adapted species and regenerate slower	AVI
Ecosite	Eco	Categorical (1 = d, 2 = e, f, h, 3 = c, g, 4 = i, 5 = j, 6 = k, l)	Compared to the reference mesic ecosite "d", lowland ecosite categories will have reduced regeneration	AVI
D. Human activity				
Distance to roads (LOG10)	Road	Continuous	Positive linear; less access for ATV's further from roads	Lineal inventory
E. Terrain characteristics				
Depth-to-water (LOG10)	DTW	Continuous	Positive non-linear quadratic; ideal moisture is in centre of distribution	WAM

Table 2
Summary of *a priori* models tested, model structure and the number of parameters (*K*). See Table 1 for descriptions of abbreviated names in the model structure.

Model #	Model name	Model structure	*K*
1	Global	α + age + standage + azim + road + lwid + eco + DTW + DTW^2	9
2	Global & interactions	α + age + azim + road + standage + lwid + eco + DTW + DTW^2 + DTW∗road + age∗DTW	11
3	Global & terrain moisture × age	α + age + azim + road + standage + lwid + eco + DTW + DTW^2 + age∗DTW	10
4	Global & terrain moisture × road	α + age + azim + road + standage + lwid + eco + DTW + DTW^2 + DTW∗road	10
5	Site characteristics	α + age + lwid + road + standage	5
6	Site & interaction	α + age + lwid + road + standage + DTW∗road + age∗DTW	7
7	Stand	α + age + standage + eco	4
8	Terrain moisture	α + age + DTW + DTW^2	4
9	Terrain moisture & interaction	α + age + DTW + DTW^2 + age∗DTW	5
10	Light	α + age + lwid + azim	4
11	Moisture & light	α + age + lwid + azim + DTW + DTW^2	6
12	Moisture, light & interaction	α + age + lwid + azim + DTW + DTW^2 + age∗DTW	7

average heights of vegetation derived from LiDAR and do not provide data on the composition of species regenerating on lines or diversity of vegetation structure, which are also important considerations for use of lines by wildlife and biodiversity (Bayne et al., 2011).

A generalized linear model (GLM) with a logit link (logistic regression) was used to analyze regeneration because the response variable used here was binary with "1" defined as regenerated to a 3 m height and "0" as not regenerated. We therefore estimated the probability that a seismic line regenerated to a 3 m height based on a set of hypothesized predictor variables. Univariate data exploration was carried out for each variable according to Zuur et al. (2010) to examine shape of variables and outliers. Depth-to-water (m) and distance to roads (m) were log10 transformed after adding a constant of 1 to limit the effects of outliers. Collinearity between predictor variables was assessed using Pearson correlation coefficients with the variable slope removed from the analysis because it was conservatively correlated with depth-to-water (DTW) at an $r^2 = 0.6$. Ecosite category and depth-to-water provided different information. Depth-to-water provided high resolution information on soil wetness, while ecosite provided additional information on nutrient status in peatland areas, which all measure close to 0 m depth-to-water, and uplands which vary in species composition and soil type. *A priori* candidate models were compared using an information-theoretic approach (Burnham and Anderson, 2002). Models were first ranked within themes of variables using Akaike Information Criteria (AIC) and the most supported model from each theme subsequently ranked amongst all themes. All statistical modelling was conducted in R (v 2.15.1, R Core Team 2012).

Model predictive accuracy and performance was estimated using Receiver-Operating Characteristic Area Under the Curve (ROC AUC) (Swets, 1988; Manel et al., 2001). Model predictions were applied to the sample plots and the optimal classification probability threshold (Manel et al., 2001) used to predict the percent of plots regenerated after 10, 30, and 50 years following the date of LiDAR collection in 2007. The optimal classification threshold identified the probability at which a plot is considered regenerated using the maximum kappa statistic for correctly classified locations (Freeman and Moisen, 2008). The R package "PresenceAbsence" (Freeman, 2007) was used to optimize the threshold, selecting the output for "MaxKappa," which showed lower bias in predicted prevalence than other threshold criteria (Freeman and Moisen, 2008). Spatial predictions of probability of vegetation regeneration to 3 m were predicted for the study area at 10, 30, and 50 years post linear disturbance to generate a map (2 m resolution) that illustrates places where linear disturbances would be more or less likely to regenerate based on our criteria. For these predictions, line width (6.8 m) and orientation (the diagonal orientation of 225°/45°) were held at their mean value.

3. Results

The most supported candidate model predicting seismic line regeneration to a 3 m height was the global model with an interaction between terrain moisture and age (Model 3; AIC weight = 0.62; Tables 2 and 3). The Receiver-Operating Area Under the Curve (ROC AUC) for this model was 0.900, indicating very good model fit and prediction. All remaining models had a much lower AIC rank (Table 3). After the global models, stand, moisture and light, terrain/moisture, light models and site characteristics were ranked in descending order (Table 3).

Standardized coefficients ranked the influence of variables explaining vegetation regeneration on seismic lines to a 3 m height. Coefficients were standardized by changing all variances to 1 and mean of 0 to allow for comparison of strength of variables. The most to least influential variables were ranked as: ecosite j (fen), depth-to-water, line width, distance to road, ecosite i (bog), ecosite e, f, h (nutrient rich), ecosite c, g (mesic and poor), ecosite k, l (wet), age, age and depth-to-water interaction, line orientation and adjacent stand age (Table 4). As ecosite d was the reference category, it was not included as a ranked variable; the other ecosite classifications were compared to "d". Time since disturbance (age of the seismic line) had less effect on vegetation regeneration to 3 m in the wettest areas (<0.3 m DTW; Fig. 3). Odds ratios describe a measure of the relationship between a variable and the response (outcome). Odds of regenerating to a 3 m height were 1.4 times greater per year per one increment increase in depth-to-water (m, log10 scale) (Table 4). Odds of regenerating to 3 m height when in a fen ecosite (j) or bog ecosite (i) were 95% and 94% less likely to reach 3 m height

Table 3
Akaiki's information criterion (AIC), changes in AIC (ΔAIC) relative to the most supported model, and Akaike weights (w_i) for the most supported model in each theme hypothesized to influence seismic line recovery to 3 m vegetation height. 3 m = GLM (logistic) probability to 3 m. The most supported model is in bold font.

#	Model name	AIC	ΔAIC	w_i
1	Global	428.6	4.1	0.08
2	Global & interactions	426.3	1.7	0.26
3	**Global & terrain moisture × age**	**424.5**	**0**	**0.62**
4	Global & terrain moisture × road	430.6	6.0	0.03
5	Site	627.8	203.2	<0.001
6	Site & interaction	497.1	72.6	<0.001
7	Stand	461.4	36.9	<0.001
8	Terrain moisture	493.2	68.7	<0.001
9	Terrain moisture & interaction	487.9	63.3	<0.001
10	Light	619.7	195.2	<0.001
11	Moisture & light	485.8	61.3	<0.001
12	Moisture, light & interaction	479.9	55.4	<0.001

Table 4
Summary of Beta (β) coefficients, standard errors (S.E.), standardized coefficients and odds ratios of unstandardized variables for the variables in the most supported model (Model 3) describing probability of reaching a 3 m vegetation height on conventional seismic lines (see Table 2 for description). Variables are ordered in decreasing importance based on standardized coefficients and the most important variable is bolded.

Variable	β	S.E.	Standardized coefficients	Odds ratio
DTW	4.06	1.60	15.1	57.97
DTW^2	−5.22	1.65	−6.5	0.01
Ecosite e, f, h	−0.97	0.37	−3.7	0.37
Ecosite c, g	−2.44	0.40	−3.0	0.09
Ecosite i	−2.79	0.44	−5.1	0.06
Ecosite j	**−3.04**	**1.07**	**−21.1**	**0.05**
Ecosite k, l	−2.09	0.80	−1.0	0.12
Lwid	−0.18	0.09	−12.6	0.84
Road	0.51	0.21	8.2	1.67
Age	0.06	0.03	0.9	1.06
Age × DTW	0.31	0.13	0.6	1.36
Stand age	−0.004	0.005	−0.3	1.00
Azim	−0.99	0.33	−0.4	0.37

than an upland ecosite, respectively (d; Table 4). Depth-to-water had a strong quadratic relationship with seismic line regeneration, peaking in regeneration to 3 m at a depth-to-water of ~2.5 m after a 10 years period and plateauing when >~2 m after a 30-year period (Table 4, Fig. 3). Regeneration to 3 m was 1.7 times more likely per 10 km distance from a road and 16% less likely per 1 m increase in line width (Table 4, Fig. 3). Finally, probability of regeneration increased as line bearing approached an east–west orientation, and increased marginally when adjacent stand age was younger (Table 4).

Optimal classification threshold probability considering a site regenerated to a 3 m height was 0.96. Using this threshold, 86% of sampled sites (existing linear footprints) were predicted to remain below a 3 m height by the year 2017, 70% by 2037 and 36% by 2057 (Table 5, Fig. 4).

Table 5
Percentage of 2 × 50 m random sample sites regenerated to a 3 m height using a LiDAR-derived canopy height model and optimal classification threshold of 0.96. The year 2007 indicates the actual results based on the LiDAR-derived canopy height model.

Year	Percentage regenerated to 3 m height
2007 (date of LiDAR)	**14**
2017	13.8
2037	30.1
2057	64.3

4. Discussion

4.1. Factors affecting regeneration of seismic lines

We demonstrated the value of using of LiDAR data to quantify regeneration of vegetation on seismic lines. The most supported models indicated that excessive moisture identified by Wet Areas Mapping, particularly in the unique conditions of fens, limited regeneration to 3 m mean vegetation height. Indeed, disturbed fens were unlikely to regenerate to a 3 m height even after 50 years. Sites where regeneration was predicted to occur most quickly was in mesic sites with 2–3 m depth-to-water. As there were relatively few xeric sites in our data set, the confidence of our regeneration conclusions for xeric (sandy) sites is weaker than for wet sites, but suggested lower recovery rates in the most xeric sites. Differences in the severity of soil disturbance due to advances in clearing techniques over time may also have a role in the interaction between depth-to-water and time since disturbance.

Wet Areas Mapping was a useful variable for modelling forest regeneration even though ecosite also has site wetness implicit in its makeup. The inclusion of both ecosite and depth-to-water far exceeded the predictive capability of either alone. This could be due to the fact that depth-to-water cannot adequately distinguish between wetlands (e.g. bogs and fens) with a low depth-to-water (i.e. 0 m; pers. com Barry White), or the sites at the drier

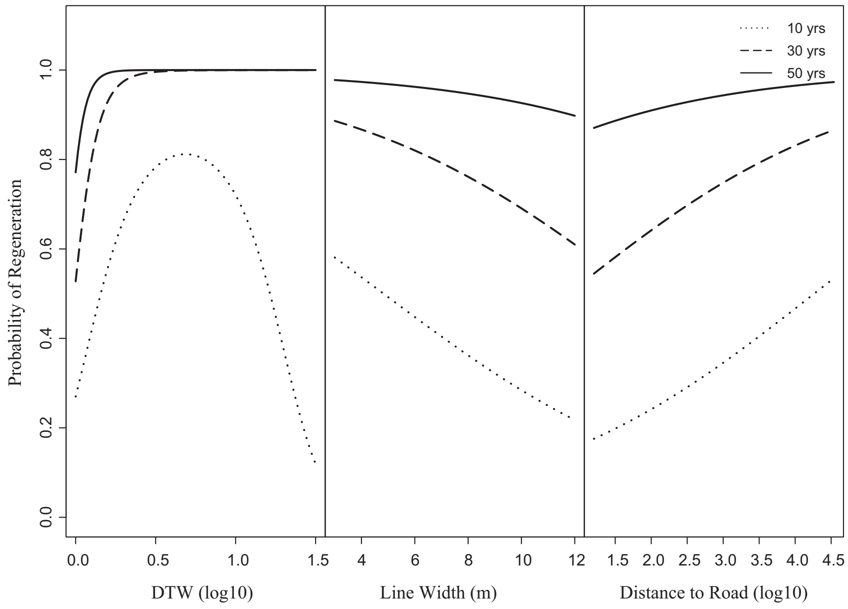

Fig. 3. Probability of forest recovery to 3 m average height after 10 (dotted line), 30 (dashed line), 50 years (solid line) dependent on depth-to-water (log10 + 1 transformed), line width (m) and distance to the nearest road (log10 + 1 transformed) as predicted by the top-selected regeneration model for the reference ecosite “d”. (Explanatory variables were held at their mean values).

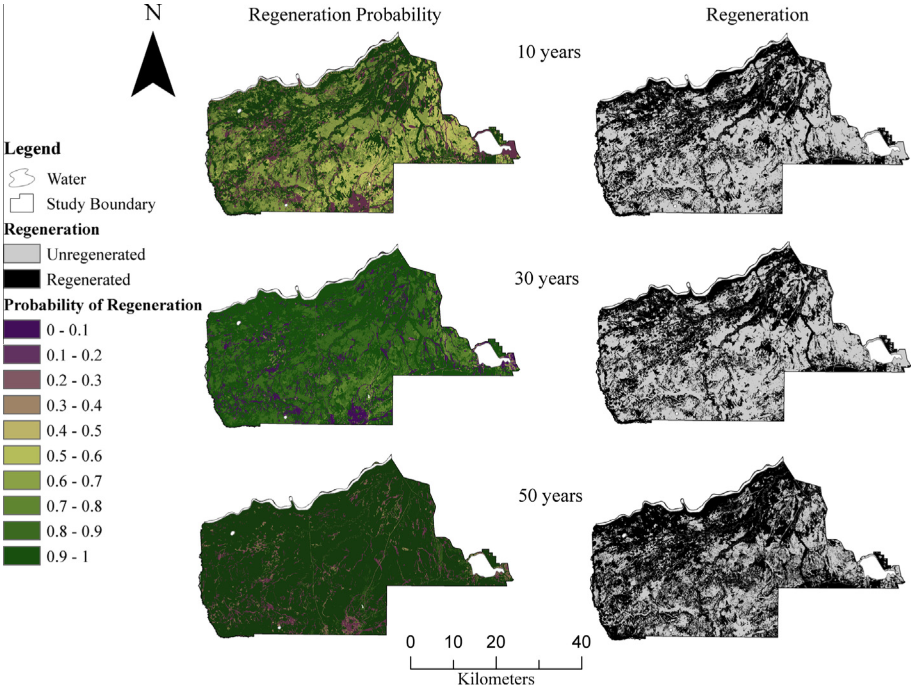

Fig. 4. Maps illustrating the potential regeneration probabilities (left) and presence absence of regeneration to a 3 m height if disturbed by conventional seismic line exploration after 10, 30 and 50 years post-disturbance. Presence absence of regeneration determined using an optimal classification threshold (MaxKappa). Line width and orientation were held at their mean values (6.8 m, 45°).

end of the spectrum, while ecosite can provide this distinction. Conversely, ecosite variation alone was not capable of explaining fine-scale variation in moisture supply that was represented by Wet Areas Mapping.

Lines in fen ecosites had more delayed regeneration than bogs. Fens have higher nutrient levels than bogs, usually as a result of flow of water that was in contact with the mineral rich deposits (Vitt, 1994). These fens are characterized by brown mosses with lower abundance of the *Sphagnum* species that build hummocks (Vitt, 1994) that are elevated above the general water table; furthermore, fens are often wetter during times of snow melt and heavy rainfall as more water flows into and through fens compared to bogs (Vitt, 1994). Industrial techniques that smooth and depress the surface of fens make them very slow to establish hummock-forming *Sphagnum* (Caners and Lieffers, 2014). Depressing the surface of fens exacerbates the flooding of microsites after heavy summer rains with flooding being detrimental to rooting of trees (Grossnickle, 2000).

Stand composition within the study area is largely driven by local variation in moisture and nutrients (Beckingham and Archibald, 1996). Previous studies of seismic line regeneration have found limited to slow rates of regeneration in wet lowland sites (Revel et al., 1984; Lee and Boutin, 2006; Bayne et al., 2011) with conifer regeneration also much slower than aspen regeneration, as aspen reproduce successfully from root suckers. Our results support this finding. A seismic line in the upland ecosite d was much more likely to regenerate than a line in a bog or especially a fen ecosite.

Our data suggest that seismic lines with narrow width have improved vegetation regeneration. Wider lines should experience increased solar radiation and therefore, improved growing conditions, for early regrowth. Exposure to excessive light may, however, lead to desiccation in moisture-limited sites. Wider lines are also more likely to have been cleared by more intrusive machinery and are prone to increased traffic by off-road vehicles that leads to more severe disturbance of the forest floor. Light, however, may be limiting for narrow (<3 m wide) lines not studied in this analysis. Line orientation also plays a role in light availability, and our results suggest that lines having an east–west orientation regenerated marginally faster than north–south lines. The shade of east–west lines might reduce competition from shade-intolerant shrubs and herbs, thereby speeding the regeneration of trees. Improved regeneration on narrow lines is compatible with recommendations to limit line width to reduce effects on boreal wildlife behaviour (Machtans, 2006; Bayne et al., 2011).

Seismic lines that were further from roads experienced higher rates of regeneration. This relationship is likely due to reduced vehicular traffic, particularly from ATVs (Revel et al., 1984). Lee and Boutin (2006) found established vehicular tracks in 20% of the seismic lines they studied within 35 years from clearing. Continued use from off-highway vehicles, including snow mobiles, can increase damage to young seedlings, erosion, soil compaction, and water channelization (Revel et al., 1984). Although distance to road is only a proxy for ATV use, these results support the need for access management of seismic lines near roads.

It was surprising that time since disturbance was not a stronger predictor of regeneration on its own. The decadal resolution of time since disturbance may have contributed to this result, however, a number of previous studies have found differential rates of recovery along seismic lines (Revel et al., 1984; Lee and Boutin, 2006; Bayne et al., 2011), suggesting that age alone is going to be a poor proxy for predicting line recovery in heterogeneous boreal forests. An interaction between time since disturbance and depth-to-water (Model 3, Table 2) may therefore better account for low recruitment in wet sites than using time alone. Additionally, differences in the severity of clearing techniques between decades may support the interaction between depth-to-water and time since disturbance.

Overall, a 3 m height benchmark for seismic line regeneration gives a rational criterion that can be easily applied and measured quickly by land use practitioners in the field or via remote sensing data like LiDAR. While the 3 m criterion is originally from local forestry standards for wildlife, the 3 m height focuses on documenting tree regeneration since it is higher than most shrubs.

4.2. Spatial patterns of regeneration potential

Areas adjacent to major river channels, such as the Athabasca and Hangingstone River, illustrated high probabilities of regeneration even 10 years post-disturbance, but showed lower regeneration probabilities in wet sites with lowland ecosites (i, j, k, l). The model suggests that if re-disturbance (i.e. fire, re-clearing, motorized access) does not occur, much of the landscape will regenerate after 50 years post-disturbance. Nevertheless, there are sites with low regeneration probabilities even after 50 years (Fig. 4).

4.3. Implications for conservation

Our results suggest that approximately one-third of existing conventional seismic lines on the landscape will fail to regenerate to a 3 m height after 50 years. Given that industrial developments are adding 2875 km of disturbance each year to the province (Komers and Stanojevic, 2013), the current rate of development, in conjunction with the slow rate of regeneration, will make reaching federal targets for woodland caribou challenging if legacy seismic lines are not reclaimed. This work highlights the utility of high resolution (LiDAR-derived) data to both collect data on regeneration patterns and derive an important variable of terrain moisture indices i.e. Wet Areas Mapping. Use of an extensive dataset like LiDAR can help address landscape and local scale questions relevant to ecological issues, particularly for remote areas where field sampling may be challenging. The modelling component of our work, however, predicts recovery using a range of driving variables which are necessary to accurately make forward projections. Our work also suggests that most mesic sites are likely to regenerate naturally without treatment if left undisturbed, while dry and especially wet sites could experience long delays in regeneration. In particular, fens could be delayed for extended periods. Most likely, fens are fundamentally altered after clearing for seismic assessment, and these habitats are going to be a major challenge for future restoration (Caners and Lieffers, 2014). Model predictions estimating regeneration probability are particularly valuable for estimating current and especially future forest regeneration trajectories on linear disturbances which are a conservation concern and a focus for restoration and planning by government, industry and conservation organizations. Prioritizing restoration actions in a spatially-explicit manner (Noss et al., 2009), considering costs and effectiveness of treatments and distance to roads is an important next step in achieving conservation goals.

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