Predicting Patterns of Regeneration on Seismic Lines to Inform Restoration Planning in Boreal Forest Habitats

by

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Abstract

Mapping of oil reserves involves the use of seismic lines (linear disturbances) to determine size of reserves. These linear disturbances fragment forests and in many cases fail to regenerate trees even decades following their use. With the continued rise in anthropogenic disturbances, regeneration of seismic lines is necessary for the conservation of biodiversity. Little is known, however, about how local and landscape factors affect natural recovery of trees and shrubs on seismic lines. I investigate factors affecting early forest regeneration using LiDAR, forest stand databases and a disturbance inventory of 4350 km of seismic lines over a 1,806 km^2 region (density of 2.4 km/km^2) of northeast Alberta. Regeneration to a height of at least 3 m or to 50% of the adjacent stand were inversely related to terrain wetness, line width, distance from 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 fail to recover even after 50 years post-disturbance. Predictions of future regeneration rates on existing lines suggested that up to 50% of existing linear disturbance footprints in this boreal landscape will remain un-regenerated 50 years later. I then used predictions of vegetation regeneration on seismic lines to 3 m height 10, 30, and 50 years post-disturbance for optimizing restoration to benefit woodland caribou. I incorporated costs for bitumen pay thickness, linear feature density, distance to nearest road and regeneration probability, while targeting restoration priority areas for woodland caribou. Marxan with Zones was used to configure seismic lines into 3 zones: active restoration (reclamation), passive restoration (natural regeneration), and available. Through prioritization of restoration of seismic lines, millions of dollars can be saved while improving woodland caribou habitat and reducing the risk of re-disturbance from future oil sands development. This thesis

effectively demonstrates methodology to assess the regeneration of vegetation on seismic lines and quantitatively optimize restoration of these disturbances. This work can directly support landscape management initiatives concerning linear footprint within Alberta Environment and Sustainable Resource Development.

Preface

Chapter 2 of this thesis has been submitted for publication by C. K van Rensen, S.E. Nielsen, B. White, T. Vinge and V. J. Lieffers, "Natural regeneration of forest vegetation on seismic lines in boreal habitats," in *Biological Conservation*. I was responsible for concept formation, data collection, analysis and the manuscript composition. S. E. Nielsen assisted with analysis. Edits and concept formation were provided by S.E. Nielsen, B. White, T. Vinge and V. J. Lieffers. S. E. Nielsen and V. J. Lieffers were the supervisory authors and were also involved manuscript composition.

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Chapter 1: General Introduction

1.0 Background

Globally, habitat loss and land conversion are some of the largest contributors to biodiversity loss (Pimm and Raven, 2000; Tilman et al., 2001, Foley et al., 2005; Cardinale, 2014). Due to a wealth of natural resources, Alberta's Boreal forest experiences pressure from competing land uses including energy development, forestry, agriculture and human expansion. In Alberta, there has been an increasing trend to incorporate elements of biodiversity in planning and policy to address the cumulative impacts of such activities. For example, the Lower Athabasca Regional Plan (LARP) developed by the Alberta government in 2012 set desired economic, environmental and social outcomes and objectives for the region in order to provide guidance to decision-makers. In particular, the Lower Athabasca region, located in northeastern Alberta, has experienced extensive oil sands development in the past 50 years, having been relatively unperturbed by anthropogenic disturbances previously. One of the strategies in LARP (2012) is the timely and progressive reclamation of disturbed lands. With anthropogenic disturbance related to oil sands development accumulating on the landscape of northeastern Alberta since the 1950s, and projected increases in production in the future, restoration of native vegetation is critical to maintain biodiversity. Habitat restoration and conservation planning should be informed by an understanding of the ecological processes, such as succession, occurring within this region of the Boreal forest.

1.1 History of Oil Sand Development in Northeastern Alberta

The Athabasca oil sands deposit in northeastern Alberta is among the largest oil sands deposits in the world (Camp, 1976, 1977; Alberta Energy, 2014). Oil sand consists of quartz sand surrounded by a layer of water and clay and covered in heavy thick oil called bitumen (Oil Sands Discovery Centre, 2014). Oil sands are recovered through surface mining or in situ technology (drilling), after, which, valuable bitumen can be extracted (Oil Sands Discovery Centre, 2014). About 20% of the oil sands in the Athabasca deposit can be surface mined (< 70 m deep), while 80% require in situ techniques that heat and extract the bitumen in place and then pump it to the surface (Oil Sands Discovery Centre, 2014). The most common in situ technique is Steam Assisted Gravity Drainage (SAGD), which uses two horizontal wells for extraction (Schneider and Dyer, 2006). Surface mining, also known as open-pit mining, has garnered greater negative attention for its environmental impacts, but in situ methods affect a larger land base of the boreal forest (Jordaan et al., 2009).

Before in situ extraction can occur, the location and extent of bitumen resources must be defined through exploration of the below-surface geological formations. Exploration is done through a seismic assessment (Alberta Energy, 2014), which creates seismic sound waves for reserve mapping. To facilitate a seismic assessment, linear corridors are cleared through the forest, referred to as seismic lines. The initial exploratory phase is accomplished through two-dimensional seismic (2D), which generates seismic waves that are recorded for coarse delineation of bitumen resources (Schneider and Dyer, 2006; Lee and Boutin, 2006). For accurate placement of the horizontal wells, three-dimensional seismic (3D) is necessary for detailed 3D models of the deposit. 3D seismic lines, typically < 3 m wide, are laid out (often ≤100 m spacing) in a cross-hatch pattern (Schneider and Dyer, 2006), being higher in density and narrower than 2D seismic. In some instances, 4D seismic is conducted in which seismic analyses are repeated to give changes in deposits over time (OPTI Canada, 2000). This thesis focuses on 2D seismic (Fig.1.1).

To enable access for operators and equipment to travel along both a source line to set off seismic charges and a receiver line for recording data, past practices involved the clearing of straight conventional 2D seismic lines, typically 6-8 m wide, through kilometers of forest using bulldozers (MacFarlane, 2003; Schmidt, 2004; Lee and Boutin, 2006). This process removed all trees and stumps, and frequently would disrupt the top soil (MacFarlane, 2003). In response to concerns regarding slow or inconsistent vegetation recovery, practices were adopted in the late-1990s to reduce the impact of conventional seismic lines through narrower lines, which were <5.5 m wide, referred to as "low impact seismic" (LIS; Schmidt, 2004; AECOM, 2009; CAPP, 2014). LIS attempts to minimize ground disturbance through low pressure vehicles, non-mechanical line cutting methods, and meandering clearing patterns, amongst other practices, but costs ~30-50% more than conventional methods (CAPP 2014). Currently, the use of LIS is widespread, but a persistent legacy of conventional seismic lines remains on the landscape (Lee and Boutin, 2006).

1.2 Recovery of Seismic Lines

An analysis of northeastern Alberta suggests that even after 35 years, ~64% of conventional seismic lines (5-8 m wide) remained cleared of trees, covered only with grass and herbs (Lee and Boutin, 2006). While other aspects of SAGD operations (i.e. well pads) are required to be reclaimed to equivalent land capability under the Environmental Protection and Enhancement Act (AESRD, 2014), there are no such requirements for seismic lines (pers. comm. Taras Pojasok, ESRD). Traditionally, seed mixes containing agronomic grasses and legumes were applied to achieve vegetation cover (Alberta Energy and Natural Resources, 1979). This practice may have reduced the establishment of native tree and shrub species following line clearing. Natural regeneration of conventional seismic lines varies in vegetation height and composition and is not simply a function of line age (Revel et al., 1984; MacFarlane, 2003; Bayne et al., 2011; Lee and Boutin, 2006). As one of the most extensive anthropogenic features in Alberta's boreal forest, unrecovered seismic lines contribute substantially to the existing footprint of linear disturbances, which also include roads, pipelines, transmission lines and trails. The high density of seismic lines in northeastern Alberta has dissected the forest; concern for the condition of boreal species has drawn attention to the importance of restoration of these landscape features.

Natural re-vegetation on highly disturbed sites can depend on chance occurrence of seed availability, favorable conditions for recruitment and an absence of competing non-native species (Standish et al., 2007). Active restoration, using a variety of silvicultural techniques, can therefore be necessary for the landscape regeneration of woody vegetation on seismic lines in particular sites. Because the number of degraded sites and thus cost is too high to reasonably apply restoration efforts to every line at once, a triage or prioritization of sites (linear disturbances) will be used to maximize the use of available resources (time and money) for restoration (Noss et al., 2009). A triage approach has previously been applied to restoration efforts where restoration is concentrated to moderately disturbed sites that can be restored with a high degree of success and at a low cost (Noss et al., 2009).

1.3 Impacts on Biodiversity

Linear disturbances (like conventional seismic lines) contribute to habitat loss and forest fragmentation, which expose the landscape to edge effects (Linke et al., 2008; Jordaan et al., 2009), which can diminish native biodiversity and homogenize flora and fauna on the landscape (Noss, 1993, 1990). These disturbances can also alter fundamental ecological processes, such as fire (Arienti et al., 2009). Seismic lines degrade habitat for a number of boreal wildlife species, for example, seismic lines alter the behaviour of ovenbirds (Bayne et al., 2005; Machtans, 2006; Lankau et al., 2013), marten (Bayne et al., 2011), black bear (Tigner et al., 2014) and woodland caribou (James and Stuart-Smith, 2000; Dyer et al. 2002). Open linear corridors promote the intrusion of people, including on all-terrain-vehicles, and potentially invasive species (i.e. exotic earthworms) deeper into the wilderness, which further exacerbate the pressure on native biota and disrupts the regeneration process (Cameron et al., 2007; Sanderson et al., 2012).

The plight of threatened woodland caribou (*Rangifer tarandus caribou*) is predominantly driving seismic line research, reclamation, and management by industry and government. Populations of woodland caribou have declined in the last several decades, particularly in areas of high industrial development (Sorensen et al., 2008). Wolves are the primary direct cause of decline of woodland caribou (James and Stuart-Smith, 2000; Latham et al., 2011a), and land-use alters the interactions between wolves and woodland caribou. Linear features can facilitate wolf movement, which results in higher prey detection rates that increase the hunting efficiency of wolves on caribou (Schneider et al., 2010). Regeneration of linear corridors may be necessary for the persistence of caribou in Alberta in the future.

1.4 Study Area

The Cumulative Environmental Management Association (CEMA) is a multi-stakeholder group based in the Regional Municipality of Wood Buffalo that developed a management area south of Fort McMurray to assess the impacts of oil sands development in northeastern Alberta. The Stoney Mountain area has over 12, 000 km of mapped linear disturbances in 325,631 hectares (33 townships), including seismic lines, providing an excellent setting for my study. This area falls in the Central Mixedwood Natural Subregion and the Lower Boreal Highlands Natural Subregion (Alberta Environment and Sustainable Resource Development, 2005). The shift between dry, mesic and wet terrain that occurs as uplands transition to lowlands drives the vegetation communities in the region.

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 landscape scale to assess detailed information on re-vegetation on seismic lines would be challenging and expensive, with helicopter travel required. Fortunately, rich remotely-sensed datasets, including Light Detection and Ranging (LiDAR), LiDAR-derived Wet Areas Mapping and detailed forest inventories, provided by Alberta Environment and Sustainable Resource Development exist for a large portion (180,603 ha) of the CEMA area (Fig. 1.2). LiDAR data is 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).

1.5 Objectives

There have been few studies investigating regeneration on seismic lines in northeastern Alberta and at this scale (Lee and Boutin 2006). Previous studies have demonstrated that seismic lines have increased recovery in upland regions compared to lowland bogs and fens, and soil compaction and reduced light levels can limit tree regeneration (Revel et al. 1984, Lee and Boutin 2006, Bayne et al. 2011). Nonetheless, there is still a lack of understanding of regeneration processes on seismic lines to facilitate spatially-explicit projections for restoration planning and management actions. Use of remote sensing and existing spatial (GIS) data to explore recovery patterns would therefore be beneficial by providing data to map regeneration patterns and to better understand landscape factors affecting recovery thus facilitating future predictions. In Chapter 2, I use LiDAR-derived data, forest stand inventory and a lineal inventory of disturbances to model local vegetation regeneration of seismic lines. Using modelled probabilities of regeneration, I predict future landscape patterns of regeneration of seismic lines. I use two criteria for line recovery: regeneration of vegetation to a 3 m height and regeneration to 50% of the adjacent stand height. Mapped regeneration probabilities to a 3 m height at 10, 30 and 50 years post-disturbance directly support analyses in Chapter 3.

In Chapter 3, I use the optimization software Marxan with Zones (Watts et al., 2008) to identify and prioritize key areas for restoration of seismic lines. I first divided segments of seismic lines into “planning units” to be zoned for active reclamation (active restoration), natural regeneration (passive restoration) or zones available for industrial development. Then, optimization analyses were conducted to identify configurations of restoration zones. Six different scenarios were compared, which targeted the restoration of 50% of conventional seismic lines, incorporated costs for bitumen pay thickness, linear feature density, regeneration probability and distance to nearest road while including, or not including, targets for caribou restoration priority areas. Interpreting the best optimal restoration zone configuration for each scenario allowed for estimates of cost savings for restoration of seismic lines.

My thesis is organized as two independent manuscripts. Chapter 2 was submitted to *Biological Conservation* and is in review. References and section breaks in Chapter 2 and 3 follow the requirements of this journal. Chapter 3 has not yet been submitted for publication. Otherwise, the general formatting of this thesis is consistent with the guidelines set forth by the Faculty of Graduate Studies at the University of Alberta.

Figures 1-1, 1-2

a) b)

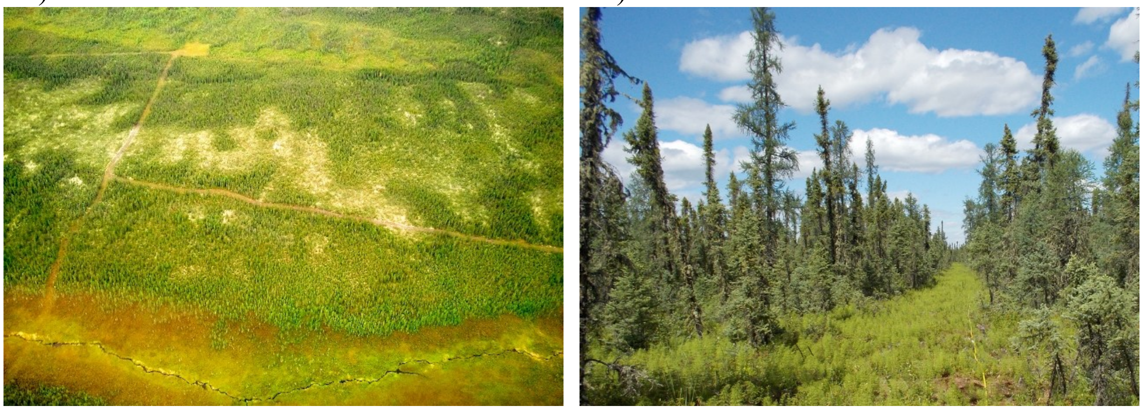

Figure 1-1. Oblique (a) and ground (b) photographs illustrating typical 2-dimensional seismic line disturbances in the boreal forests of northeast Alberta, Canada (56° 29′ 35″ N, 111° 18′ 26″ W). Photographs by C. van Rensen.

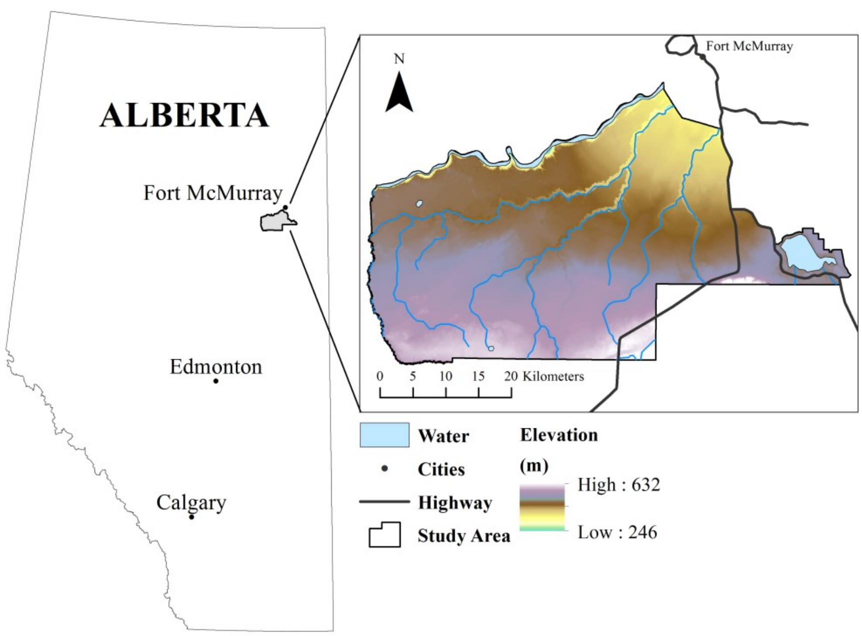

Figure 1-2. Planning region map of Stoney Mountain Area in Alberta, Canada (56° 27′ 37″ N, 111° 42′ 14″ W).

Chapter 2: Natural regeneration of forest vegetation on seismic lines in boreal habitats

1. Introduction

Increasing oil and gas development in Alberta's boreal forest has resulted in significant fragmentation of the landscape. Most extensive of these developments are seismic lines, linear forest corridors used to send vibrations from small explosions to map below-surface oil and gas deposits (Lee and Boutin, 2006, Fig.1-1). While recent technologies and best management practices have substantially reduced the width of seismic lines since the mid-1990s (Schmidt, 2004; AECOM, 2009), there is an extensive footprint of traditional seismic lines that persists (Lee and Boutin, 2006).

Treeless seismic corridors leads to habitat fragmentation and exposes the landscape to edge effects (Linke et al., 2008). Fragmentation of the boreal forest in Alberta has been shown to affect the behaviour of a number of wildlife species such as ovenbirds (Bayne et al. 2005; Machtans, 2006; Lankau et al., 2013), marten (Bayne et al. 2011, Tigner, 2012,), black bear (Tigner, 2012) 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 requiring 65% of woodland caribou habitat to be undisturbed as defined by being at least 500 m from any anthropogenic disturbance (Environment Canada, 2012), with seismic lines often representing the largest single footprint. Together with habitat conservation and predator 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 disturbance threshold for caribou was surpassed in 1992 and with the current rate of development and use of the 500 m buffer rule there will be no 'habitat' left by 2028 (Komers and Stanojevic, 2013). Understanding the factors that promote or inhibit seismic line forest regeneration is therefore critical for projecting future thresholds (federal targets) for caribou habitat and reducing fragmentation.

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 reduced 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 older seismic lines leveled the microtopography resulting in persistent changes to the vegetation as suggested by Lee and Boutin (2006). 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, *in press*). Flooding slows growth due to reduced soil temperatures that limit aeration, chemical and biological reactions (Lieffers and Rothwell, 1987; Bonan and Shugart, 1989; Levine et al., 1993). Depending upon soil moisture and soil frost, bulldozers also have the potential to compact soil, reducing soil aeration and root penetration in soils (Startsev and McNabb, 2009).

Seismic line disturbance is different than wildfire, the most frequent disturbance in the boreal forest. Recently burned areas are usually dominated by young early successional species adapted to disturbance (Rowe and Scotter, 1973) by sprouting in aspen (*Populus tremuloides* Michx.) (Frey et al., 2003) and recruitment from seed from other tree species (Greene and Johnson, 1998, Greene et al., 2007); this early recruitment largely determines the successional trajectory of boreal forest stands (Johnstone et al., 2004). 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 and the type of woody and herbaceous species vary along its length (Revel et al., 1984; Beckingham and Archibald, 1996). As seismic lines cut through existing forest stands, light availability on the line is affected by the width and orientation of seismic lines (Revel et al., 1984), which affects vegetation composition and speed of regeneration on the line. For example, shade intolerant trembling aspen, can quickly establish 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 on shaded sites.

Few studies have assessed forest recovery patterns on seismic lines (Revel et al., 1984; MacFarlane, 2003; Lee and Boutin, 2006). One challenge is the remoteness, time and cost of field research. The Government of Alberta has acquired Light Detection and Ranging (LiDAR) data for much of the forest zone of Alberta. These remote sensing data have been used to develop Wet Areas Mapping (WAM) 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). LiDAR has been used to characterize the horizontal and vertical structure of the forest canopy (Kane et al., 2013) and measure forest canopy height and gap closure (Vepakomma et al., 2010). LiDAR was also used to study behavioural responses to linear disturbances by ovenbirds and marten (Bayne et al., 2011); although age of disturbance explained some of the observed patterns in line regeneration, many of the patterns in regeneration remained unexplained. LiDAR has been shown to be very useful as a tool for measuring forest attributes, but to our knowledge the landscape patterns of vegetation regeneration on seismic lines has not been modelled using the suite of landscape information available, such as Wet Areas Mapping data.

Objectives of this paper were to use LiDAR-derived data, forest stand inventories and a lineal inventory of disturbances (Lineal Characterization Manual and Specifications, 2012) to model local vegetation regeneration of seismic lines and using those relationships to predict future landscape patterns of regeneration in northeast Alberta. In our work, we apply two different criteria for regeneration. First, we apply a 3 m rule of fixed vegetation height to define 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). Secondly, we apply a variable height criteria of regeneration to 50% of the adjacent stand canopy height, which adjusts for potential differences in regeneration between upland and lowland stands. Selecting 50% reflects a conservative assumption that a site is adequately on a recovery trajectory containing woody vegetation. Using a simple metric such as height allows for straightforward interpretation in restoration efforts.

2.0 Methods

2.1. Study Site

The study site comprises 180 603 hectares of boreal forest south of Fort McMurray within the Stoney Mountain area of northeast Alberta (56° 27′ 37″ N, 111° 42′ 14″ W, Fig. 1-2). The Stoney Mountain area has a gradual shift in elevation from 246 m to 632 m in the southeast (Fig.1-2). The area is classified as Central Mixedwood Natural Subregion with a smaller section of the Lower Boreal Highlands Natural Subregion (Alberta Environment and Sustainable Resource Development, 2005). Vegetation includes black spruce (*Picea mariana*) or larch (*Larix laricina* (Du Roi) K. Koch) dominated bogs, poor fens, rich fens and marshes in the lowland 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 (*Populus tremuloides*) poplar (*Populus balsamifera* L.), jack pine (*Pinus banksiana* Lamb.), white spruce (*Picea glauca* (Moench) Voss) or 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 month (Natural Regions Subcommittee, 2006). The study area is occupied by woodland caribou (Schneider et al., 2012). The Stoney Mountain area has ~12 000 km of linear disturbances, 4350 km of which are in our study area (Nash, 2012).

2.2. Defining of vegetation height on seismic lines

Discrete airborne 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. These data were cleaned and prepared using the software TerraScan and TerraModel with a minimum intensity of 1.41 points per square meter and classified into bare-earth (ground) and vegetation (above-ground) points within the study site. A minimum vertical accuracy of < 30 cm and horizontal accuracy of < 45 cm Root Mean Square Error, which is the square root of the average of the set of squared differences between elevation values from an independent source of higher accuracy, were achieved. To estimate canopy height we developed a digital elevation model (DEM) for the study area using linear interpolation from last return (bare-earth) points contained in a LAS Dataset (LiDAR point cloud) in ArcGIS (v. 10.1). A digital surface model (DSM) was then developed for the study area from first return (maximum height) points and the canopy height 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 cell size) using LiDAR. 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 scale to examine vegetation heights specific to conventional seismic lines.

Linear features 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 greater than 50 m in length 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. Fifty-three percent of these linear features were conventional 2-dimensional (2D) seismic lines (1448 km), which are typically wider and older than the more recent 3-dimensional (3D) seismic lines (1593 km). This study is limited to 2D lines. As described by the caribou recovery strategy (Environment Canada, 2012), adding a 500 m buffer around 2D lines resulted in 54.3% of the study area being disturbed. Buffering 3D lines and 2D lines resulted in 67% of the study area being disturbed (3D lines are concentrated to local sites and are closely spaced resulting in lower buffered footprints, while roads are few). Along 2D seismic lines we established 1043 random plots that were 2 x 50 m in size and at least 250 m apart (ArcGIS Create Random Points tool, v10.1) to ensure that they were spaced apparent to 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, but there were considerable spatial misalignments with the GIS vector layers depicting seismic line location and lineal attribute information due to inaccuracies of the other GIS layers during digitization and not the LiDAR-derived data itself (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 and thus substantially reducing error in estimation of vegetation height on the line due to adjacent forest canopy. To further reduce error from the adjacent canopy, only lines greater than 3 m in width were used, reducing the sample size to 863 plots. The oldest seismic line clearing was less than 40 years and it is highly improbable that line regeneration exactly resembled the adjacent stand in height, composition and density. For this reason, we were assured that no seismic lines were missed in the lineal inventory (pers. comm. John Nash, Greenlink Forestry Inc). Nonetheless, limiting the analysis to lines > 3 m wide reduces the chance that the adjacent canopy could have grown in and closed the gap visible in aerial photography, which could be a concern in Aspen stands. Canopy height and explanatory continuous variables were averaged across the 2 x 50 m plots.

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 2-1). Disturbance history variables included time since clearing of the seismic line (Table 2-1). 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). 80% of lines were most recently cleared in the 2000s, 18 % in the 1990s, and 1% in each of 1970s and 1980s. 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. Linear regression results from tree ring analysis indicated good consistency with year of disturbance estimates ($r = 0.76$, $df = 114$, $P<0.001$).

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 Inventory Interpretation Standards, 2005). Ecosites were grouped to uplands (d; reference, modal category); poor (c,g); mesic and nutrient rich (e, f, h); bog (i); fen (j); and wet (k,l) because of low representation of each ecosite class (Beckingham and Archibald, 1996).

Line characteristics included line width and orientation of line. There were only 2 examples of lines 15 m wide or greater and were more representative of pipelines than 2D seismic lines and were, therefore excluded from the analysis. To reduce error from the adjacent canopy on seismic lines when interpreting LiDAR heights, only lines > 3 m were used in the analysis. 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 "θ" 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 in summer seismic lines in dry, upland sites will be used more frequently compared to seismic lines that are wet (i.e. equipment is more likely to get stuck in wet sites).

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 DTW. WAM predicts water depth and is based on a set of GIS algorithms that use the LiDAR point cloud to define terrain wetness (Hiltz et al., 2012; White et al., 2012). 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 x 50 m seismic line plot.

2.4. Model Selection and Analysis

Models explaining seismic line vegetation regeneration to a 3 m height and to 50% height of the adjacent stand (stand height derived from AVI) over the 2 x 50 m plot (response variable) were developed from five different *a priori* candidate themes of variables (Table 2-2). 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. An interaction between both time since disturbance, and distance to roads, with ecosite was explored, but this dramatically increased the complexity of the models and thus, interactions with terrain wetness were deemed sufficient. It is important to note that models reflect average heights of vegetation derived from airborne LiDAR data and do not provide data on the composition of species regenerating or vegetation structure, which are also important considerations for use of lines by wildlife.

A GLM with a logit link (logistic regression) was used to analyze regeneration because the response variable was binary with "1"defined as regenerated to a 3 m height or in the second analysis to ≥50% of the adjacent canopy height and "0" as not regenerated. We therefore estimated the probability that a seismic line regenerated to a 3 m height or ≥50% of the adjacent canopy 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. *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 was estimated using ROC AUC (Manel et al., 2001). The models for each criteria (3 m and 50%) were applied to the sample plots and the optimal classification probability threshold (Manel et al., 2001) used to predict the percentage 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 by maximizing the kappa statistic by measuring the proportion of correctly classified locations after accounting for the probability of chance agreement (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 and to 50% of the adjacent stand height were created for the entire study area at 10, 30, and 50 years post linear disturbance to generate a general landscape vulnerability map that illustrates places where linear disturbances would be more or less likely to regenerate. For these predictions, line width (6.8 m) and orientation (the diagonal orientation of 225°/45°) were held at their mean value.

3.0 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 2-2, 2-3). The 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 2-3). After the global models, stand, moisture and light, terrain/moisture, light models and site characteristics were ranked in descending order (Table 2-3).

The most supported candidate model predicting seismic line regeneration to 50% of the adjacent stand height was the global model (Model 1; AIC weight=0.42; Tables 2-2, 2-3). The ROC AUC for this model was 0.754, indicating good model fit and prediction. All remaining models had a much lower AIC rank (Table 2-3). Following the global models, stand, site, terrain/moisture, moisture and light, and light models were ranked in descending order (Table 2-3).

Standardized coefficients ranked the influence of variables explaining vegetation regeneration on seismic lines to a 3 m height. 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 (poor), ecosite k, l (wet), age, age and depth-to-water interaction, line orientation and stand age (Table 2-4). 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. 2-3). Odds of regenerating to a 3 m height were 1.4 times greater per year and one increment increase in depth-to-water (m, log10 scale) (Table 2-4). 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 than an upland ecosite, respectively (d; Table 2-4). Depth-to-water had a very strong quadratic relationship with seismic line regeneration, peaking at a depth-to-water of ~2.5 m after 10 years, plateauing after ~2 m after 30 years. (Table 2-4, Fig. 2-3a). 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 2-4, Fig. 2-3a). Finally, probability of regeneration increased as line bearing approached an east-west orientation, and increased slightly if stand age was younger (Table 2-4).

The most to least influential variables for regeneration to 50% height of the adjacent stand were ranked as: depth-to-water, ecosite j (fen), ecosite k,l (wet), distance to road, line width, stand age, ecosite e, f, h (nutrient rich), ecosite i (bog), ecosite c, g (poor), age, and line orientation (Table 2-4). Time since disturbance (age of the seismic line) had a limited effect on regeneration, for every additional year since disturbance regeneration was 4% more likely (Table 2-4). Presence in a bog (i) or fen (j) ecosite reduced likelihood of reaching regeneration to 50% of the adjacent stand height by 30% or 70% compared to an upland site, respectively (Table 2-4). Depth-to-water had a very strong quadratic relationship with seismic line regeneration, peaking at a depth-to-water of ~2 m after 10, 30, and 50 years, (Table 2-4, Fig. 2-3b). Regeneration was 1.5 times more likely per 10 km distance from a road and 7% less likely for every meter increase in line width (Table 2-4, Fig. 2-3b). Finally, probability of regeneration increased as line bearing approached an east-west orientation and increased slightly if stand age was younger (Table 2-4).

The classification threshold probability to consider a site regenerated to 3 m height was 0.96 and for 50% to the adjacent stand height was 0.19. For the 3 m regeneration height criteria 86% of sampled sites (existing linear footprints) were predicted to remain un-regenerated by the year 2017, 70% by 2037 and 36% by 2057 assuming recruitment occurs on open seismic lines using the optimal classification threshold (Table 2-5). For the 50% to adjacent stand height regeneration criteria, 94% of sampled sites (existing linear footprints) were predicted to remain un-regenerated by the year 2017, 79% by 2037 and 52% by 2057 assuming recruitment occurs on open seismic lines (Table 2-5).

4.0 Discussion

4.1. Factors affecting regeneration of seismic lines

The best models indicated that excessive moisture identified by wet areas mapping, particularly in the unique conditions of fens, limited regeneration probability for both of the regeneration criteria in this study (growth to 3 m height and 50% adjacent stand height). Disturbed fens were unlikely to regenerate to a 3 m height even after 50 years; the best sites for regeneration probability occurred in mesic sites with 2-3 m depth-to-water. There was, however, evidence that regeneration to 3 m was delayed on very dry sites (> 8m) based upon the interaction between age and depth-to-water. For regeneration to 50% of the adjacent stand, both very wet (~<1 m DTW) and dry sites (~>5 m DTW) were also less likely to regenerate for 10, 30 and 50 years, and the peak regeneration was also on the mesic sites. As there were relatively few xeric sites in our data set the confidence of our regeneration conclusions for xeric sites is weaker than for wet sites. Differences in clearing techniques over time may also have a role in the interaction between depth-to-water and time since disturbance.

This is the first example of Wet Areas Mapping being used for modelling forest regeneration. Depth to water may have a relationship with soil temperature. Wet soils are typically colder, reducing the rate and efficiency of biological processes within the soil and reducing water uptake due to lower hydraulic conductivity, higher root resistance, and increased water viscosity, potentially limiting the rate of tree growth (Blanco et al., 2009). Warmer soils may decompose organic matter on the forest floor more rapidly, improving nutrient cycling (Blanco et al., 2009). Even though both ecosite and depth-to-water describe soil moisture, the inclusion of both in the regeneration model 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), and ecosite can provide this distinction.

The fen ecosites had even more delayed regeneration than bogs. Fens have higher nutrient status than bogs, usually as a result of flow of water through these systems that was in contact with the mineral rich deposits of this region (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. Industrial techniques that smooth and depress the surface of fens make them very slow to establish hummock-forming *Sphagnum spp* (Caners and Lieffers, *in press*). Depressing the surface of fens exacerbates the flooding of microsites after the heavy summer rains of this region; flooding is detrimental to rooting of most boreal forest trees (Grossnickle, 2000). The *Sphagnum* of bogs tend to raise the general level of these sites and likely shorten the period of flooding after heavy rains, thereby increasing survival of trees.

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., 2012) with conifer regeneration also much slower than aspen regeneration as aspen reproduce well from root suckers. This supports our results because a seismic line in reference mesic ecosite “d” was much more likely to regenerate than a line in a bog or fen ecosite, particularly for the 3 m height criteria. While regeneration to 50% adjacent stand height was still more likely to occur in ecosite “d” compared to any other ecosite group, differences between the two regeneration criteria are most evident for the ecosite variable than other variables tested. In some cases, depending on the combination of other site conditions, it is easier for a bog to reach 50% of the adjacent stand height than a 3 m height – presumably because of the low stature of trees in the bogs around seismic lines.

Our data suggests that seismic lines with narrow width have improved vegetation regeneration. While wider lines should experience increased solar radiation and therefore, improved growing conditions, for early regrowth, exposure to excessive light may lead to desiccation in moisture-limited sites. In addition, wider lines are more likely to have been cleared by more intrusive machinery and are prone to increased traffic by off-road vehicles that could lead to severe disturbance of the forest floor. Light, however, may be limiting for narrow (< 3m wide) lines that are characteristic of 3D seismic lines, which experience substantial shading from adjacent canopy, and these narrow lines were 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 slightly more quickly 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. The superior regeneration on narrow lines is compatible with recommendations to limit line width to reduce effects on boreal wildlife behaviour (Bayne et al., 2012; Machtans, 2006).

Seismic lines that were further from roads experienced higher rates of regeneration, likely because of reduced vehicular traffic, particularly from ATVs, (Revel et al., 1984) further from main access roads. 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.

As it is obvious that tree height is incremental with time, it was surprising that time since disturbance was not a stronger predictor of regeneration on its own. Possibly, the decadal resolution of time since disturbance was not precise enough in the models as height growth usually follows a logistic growth curve with age (Bokalo et al. 2013), including a potential lag time for recruitment following disturbance. An interaction between time since disturbance and depth-to-water may therefore better account for low recruitment in wet sites than time alone. Additionally, differences in the severity of clearing techniques between decades may support an interaction between depth-to-water and time since disturbance.

Model selection from both regeneration criteria reveal similar strengths and direction of factors affecting regeneration on seismic lines. This is somewhat surprising given that the 3 m criteria uses a fixed height threshold and the 50% criteria uses a height relative to the surrounding forest. Probabilities of regeneration were higher across the landscape, however, for the 3 m height criteria (Fig.2-4, 2-5). As most of the lines were cut in areas without recent disturbances (i.e. fire), then there were few lines where the 50% height benchmark would be young and very short. Overall, however, we prefer the 3 m criteria as we think that this benchmark gives a rational criterion that can be applied by land use practitioners. While the 3 m criteria is borrowed from forestry standards for wildlife, 3 m height filters out many of the shrubs and focuses regeneration on trees. However, this criteria may be less effective in bogs where the native trees never reach three meters in height.

4.2. Spatial patterns of regeneration potential

For the 3 m height criteria, areas adjacent to large stream channels showed high probabilities of regeneration even 10 years post-disturbance. This pattern was not evident for regeneration to 50% of the adjacent stand height. In drier upland sites (ecosites b,c,d,g), aspen or jack pine dominated stands can reach 30 m in height, requiring average heights of 15 m to reach regeneration criteria leading to near 0 regeneration probabilities at the most productive sites for tree regeneration even after decades. Both criteria showed lowed regeneration probabilities in wet sites with lowland ecosites (i, j, k, l). Regeneration patterns for each criteria resembled each other more closely when using the optimal threshold criteria to map predicted presence/absence of regeneration for 10, 30 and 50 years post-disturbance (Fig. 2-5). 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, 2-4, 2-5).

4.3 Implications for Conservation

Our results predicted that approximately half of existing 2D seismic lines on the landscape will remain un-regenerated after 50 years, according to the criteria outlined (Table 5). Given that industrial development adds 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 historic seismic lines are not reclaimed. This work highlights the utility of high resolution (LiDAR-derived) data to both collect data on regeneration and derive an important variable of terrain moisture indices i.e. Wet Areas Mapping. 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. 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.

Tables 2-1; 2-2; 2-3; 2-4; 2-5

Table 2-1

Explanatory variables included in the generalized linear models (GLMs) with a logit link. 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)	Ecosite D have the greatest regeneration compared to other ecosite groups	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 2-2
Summary of models for general linearized models (GLMs) with logit link and Gaussian distribution 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	14
2	Global & Interactions	α+ age+azim+road+standage +lwid+ eco+ DTW+ DTW^2 +DTW*road+ age*DTW	16
3	Global & Terrain Moisture x Age	α+ age+azim+road+standage +lwid+ eco+ DTW+ DTW^2+age*DTW	15
4	Global & Terrain Moisture x Road	α+ age+azim+road+standage +lwid+ eco+ DTW+ DTW^2 +DTW*road	15
5	Site Characteristics	α +age+lwid+road+standage	5
6	Site & Interaction	α +age+lwid+road+standage + DTW*road+ age*DTW	8
7	Stand	α +age+standage+eco	5
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

Table 2-3
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. 3 m= GLM (logistic) probability to 3 m, 50% = GLM (logistic) height online to stand ratio to 50%. Values for best model are bolded.

#	Model Name	AIC		ΔAIC		w_i	
		3 m	50%	3 m	50%	3 m	50%
1	Global	428.6	**379.3**	4.1	**0**	0.08	**0.42**
2	Global & Interactions	426.3	382.7	1.7	3.4	0.26	0.08
3	Global & Terrain Moisture x Age	**424.5**	381.3	**0**	2.0	**0.62**	0.16
4	Global & Terrain Moisture x Road	430.6	380.7	6.0	1.4	0.03	0.21
5	Site	627.8	388.4	203.2	9.1	<0.001	0.004
6	Site & Interaction	497.1	383.7	72.6	4.4	<0.001	0.05
7	Stand	461.4	382.5	36.9	3.3	<0.001	0.08
8	Terrain Moisture	493.2	398.7	68.7	19.4	<0.001	<0.001
9	Terrain Moisture & Interaction	487.9	397.1	63.3	17.8	<0.001	<0.001
10	Light	619.7	408.8	195.2	29.6	<0.001	<0.001
11	Moisture & Light	485.8	401.6	61.3	22.4	<0.001	<0.001
12	Moisture, Light & Interaction	479.9	400.0	55.4	20.8	<0.001	<0.001

Table 2-4
Summary of Beta (β) values, standard error (S.E.), standardized coefficients and odds ratios for the variables in Model 3 for 3 m height and Model 1 for the 50% of adjacent stand height regeneration criteria (see Table 2 for description). Variables are ordered in decreasing importance based on standardized coefficients and most important variables are bolded.

Variable	β		S.E.		Standard. Coefficients		Odds Ratio	
	3 m	50%	3 m	50%	3 m	50%	3 m	50%
DTW	4.06	**6.42**	1.60	**2.60**	15.1	**33.2**	56.98	**600.12**
DTW^2	-5.22	-7.08	1.65	3.82	-6.5	-12.2	0.01	0.0008
Ecosite e,f,h	-0.97	-0.51	0.37	0.53	-3.7	-2.7	0.37	0.60
Ecosite c,g	-2.44	-0.47	0.40	0.47	-3.0	-0.8	0.09	0.62
Ecosite i	-2.79	-0.36	0.44	0.48	-5.1	-0.9	0.06	0.70
Ecosite j	**-3.04**	-1.19	**1.07**	1.11	**-21.1**	-11.3	**0.05**	0.30
Ecosite k, l	-2.09	-14.7	0.80	600.2	-1.0	-10.0	0.12	0.0000004
Lwid	-0.18	-0.07	0.09	0.08	-12.6	-6.7	0.84	0.93
Road	0.51	0.40	0.21	0.25	8.2	8.8	1.67	1.49
Age	0.06	0.04	0.03	0.02	0.9	0.8	1.06	1.04
Age x DTW	0.31	NA	0.13	NA	0.6	NA	1.36	NA
Stand age	-0.004	-0.03	0.005	0.01	-0.3	-3.1	1.00	0.97
Azim	-0.99	-0.32	0.33	0.35	-0.4	-0.2	0.37	0.73

Table 2-5
The percentage of 2 x 50 m sites from a random sample that are considered regenerated to either 3 m height or 50% of the adjacent stand height using a LiDAR-derived canopy height model based on optimal classification thresholds. The bolded values indicate the actual results based on the LiDAR-derived canopy height model.

Year	3 m height (%)	50% adjacent stand height (%)
2007(date of LiDAR)	**14**	**8.6**
2017	13.8	6.3
2037	30.1	20.7
2057	64.3	48.3

Figures 2-3; 2-4; 2-5

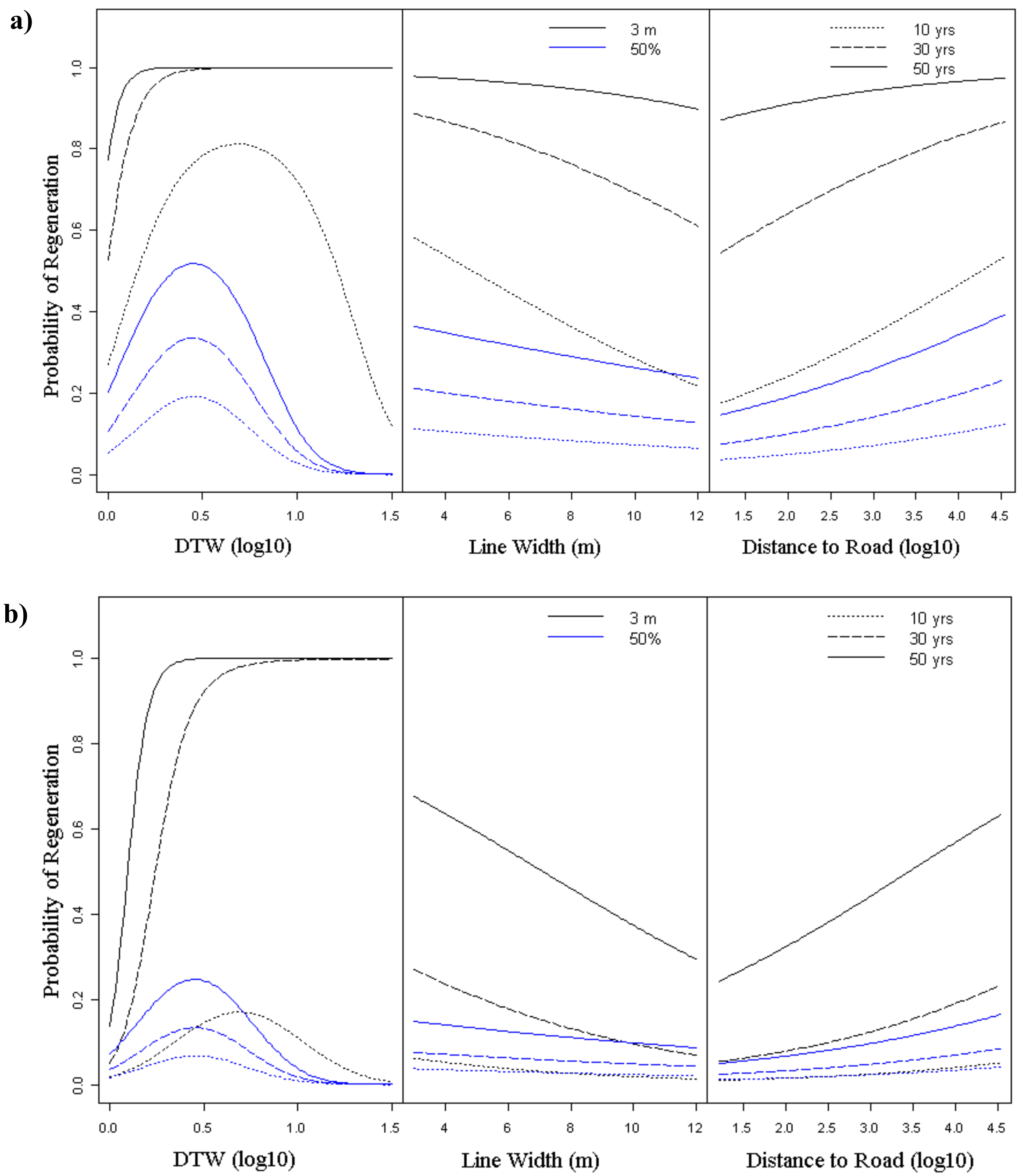

Figure 2-3. Probability of forest regeneration to 3 m average height (black) and 50% of the adjacent stand average height (blue) after 10 (dotted line), 30 (dashed line), 50 years (solid line) dependent on depth-to-water (log10+1 transformed), line width (m) and distance to the nearest road (log10+1 transformed) as predicted by the top-selected regeneration model for the reference ecosite "d" (A) and a fen ecosite "j" (B; see Table 2). Explanatory variables were held at their mean values).

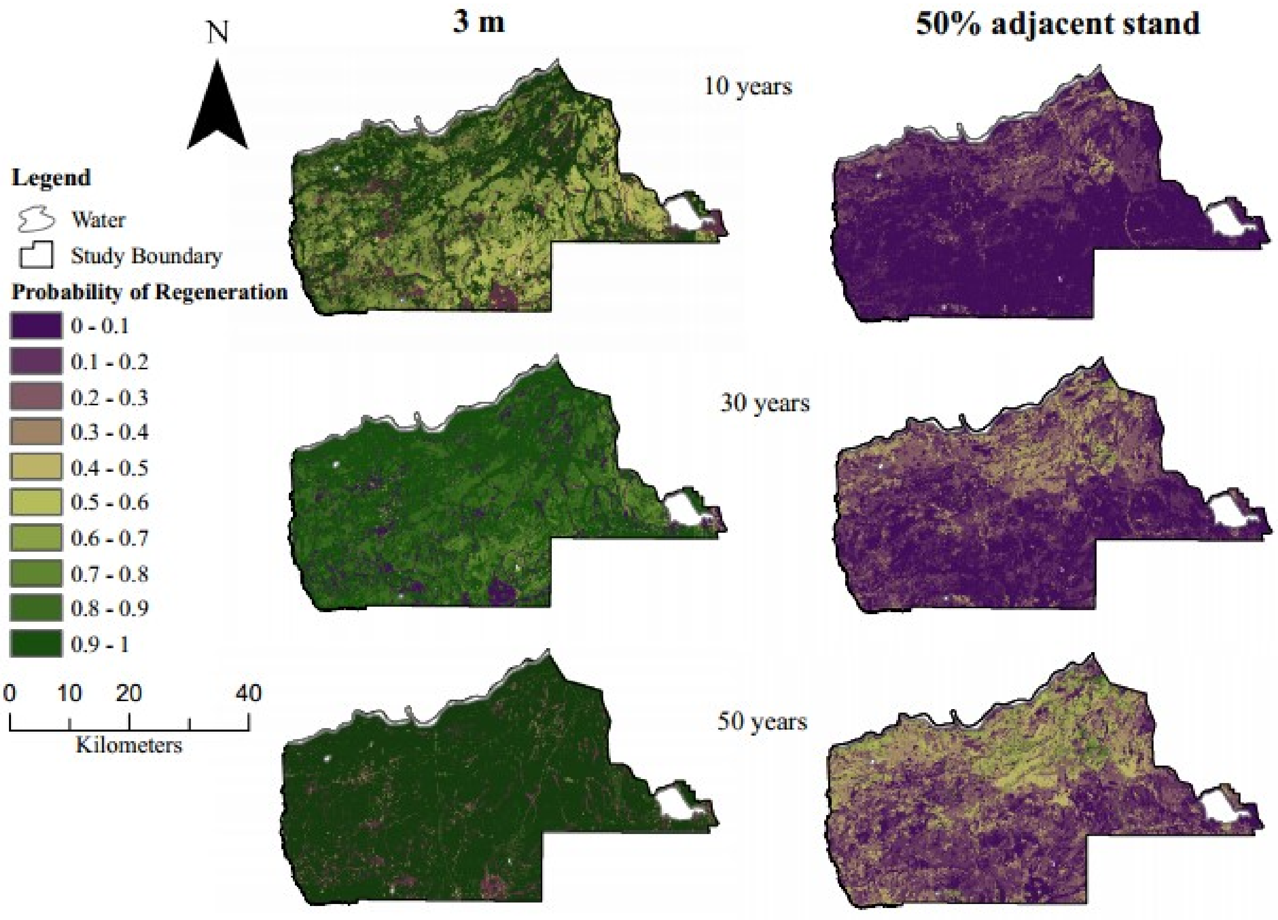

Figure 2-4. Maps illustrating disturbance vulnerabilities and potential regeneration probabilities if disturbed by 2-D seismic line exploration for 3 m height or 50% of the adjacent stand after 10, 30 and 50 years post-disturbance. Line width and orientation were held at their mean values (6.8 m, 45 ^{0}).

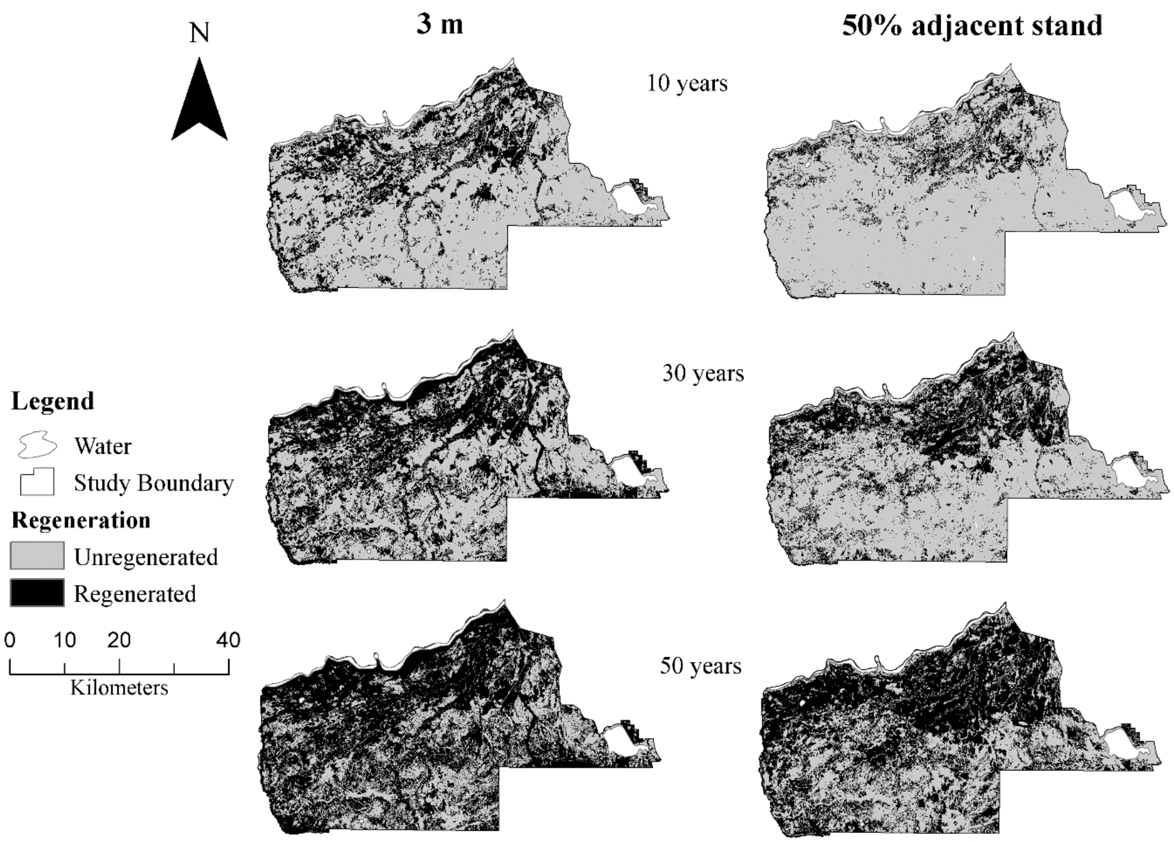

Figure 2-5. Maps illustrating disturbance vulnerabilities and potential recovery probabilities if disturbed by 2-D seismic line exploration. Maps illustrate predicted presence and absence of regeneration to 3 m height (left) or 50% of the adjacent stand height (right) after (a) 10, (b) 30, and (c) 50 years post-disturbance using optimal classification thresholds (MaxKappa). Line width and orientation were held at their mean values (6.8 m, 45 ^{0}).

Chapter 3. Landscape optimization of seismic line restoration in Alberta's oil sands

1.0 Background

Oil sands development in Alberta's boreal forest has significantly increased forest fragmentation (Komers and Stanojevic, 2013). In many cases, the most extensive footprints of disturbance are seismic lines, linear forest corridors used to send energy waves produced from small explosions or vibrations to map below-surface petroleum deposits. While recent technologies and best management practices have reduced the width and impact of seismic lines (Schmidt, 2004; AECOM, 2009), there are still many traditional (legacy) seismic lines (average width ~5-8 m) that persist as open linear corridors (Lee and Boutin, 2006). Most traditional seismic lines are no longer needed for exploration, but variation in regeneration rates of trees on these lines results in extensive overall footprints, often with vegetation on seismic lines that differs from the adjacent interior forests (Revel et al., 1984; MacFarlane, 2003).

Leaving seismic corridors treeless leads to habitat fragmentation of boreal forests and exposes adjacent habitats to edge effects (Linke et al., 2008). This affects the behaviour of wildlife species such as ovenbirds (Bayne et al., 2005; Machtans, 2006; Lankau, 2013), marten (Bayne et al., 2011, Tigner, 2012,), black bear (Tigner, 2012) and woodland caribou (James and Stuart-Smith, 2000; Dyer et al., 2002; Latham et al., 2011a). The decline of woodland caribou has been most contentious, with the Federal government initiating a caribou recovery strategy that requires 65% of woodland caribou habitat to be undisturbed as defined by being at least 500 m from any anthropogenic disturbance (Environment Canada, 2012). The extensive network of seismic lines with these buffers often represents the largest single disturbance footprint for caribou. Together with habitat conservation and predator management, regeneration of seismic lines is considered a priority and necessary for sustaining Alberta's threatened woodland caribou herds (Schneider et al., 2010). To benefit woodland caribou, it may help to reduce the line of sight and ease of travel for their predators (i.e. wolves and black bear), which could be achieved through structural manipulations (i.e. coarse woody debris) without line regeneration.

Nonetheless, seismic line regeneration can improve habitat quality, reduce line of sight and access, and benefit other elements of biodiversity that prefer interior habitats.

Seismic line reclamation is not currently required by industry in Alberta (pers. comm. Taras Pojasok). Although new seismic lines now have a reduced footprint, the provincial government is under pressure to reduce the existing footprint in order to manage biodiversity, particularly with attention given to woodland caribou. Active reclamation of seismic lines is more expensive on a per hectare basis than conventional cut block silviculture, with costs ranging from $3066-4466/km of treated line (pers. comm. Tim Vinge). This estimate includes site preparation, mounding and planting, but may severely underestimate total costs once access and monitoring are considered. With thousands of kilometers of seismic lines, it is not realistic that all conventional seismic lines will be actively reclaimed at one time.

Conservation often competes with other human interests (Margules et al., 2002), and the South Athabasca oil sands region is one of the busiest places in Alberta with respect to in situ energy development. In situ (in place) technology is used to recover bitumen present in the oil sands layer deeper than 75 meters from the surface (Oil Sands Discovery Centre, 2009). Effort to restore sites that are likely to be re-disturbed for energy exploration in the near future is not sensible economically, nor would it be beneficial to creating suitable habitat for wildlife. Furthermore, it is not sensible to restore lines likely to regenerate naturally in the short term, nor to restore lines in which reclamation efforts may be futile. This has been referred to as a triage approach, where in this case restoration is concentrated to moderately disturbed sites that can be restored with a high degree of success and at a low cost (Noss et al., 2009). It follows, then, that selection of lines for restoration should be optimized (prioritized).

Restoration can range from passive to active; passive restoration includes leaving a site to recover without intervention (Zahner, 1992) and active restoration includes some form of human intervention or management, often at high costs (Noss et al., 2009). Natural re-vegetation on highly disturbed sites can depend on the chance occurrence of seed availability, favorable conditions for recruitment and an absence of competing non-native species (Standish et al 2007). In northeastern Alberta, conventional seismic lines take from ~10 to over 50 years to reach an average 3 m height depending on disturbance history, ecological conditions and terrain wetness (van Rensen et al., in review). Prioritization is necessary to make the best use of resources and to determine whether sites should be zoned for active or passive restoration (Noss et al., 2009). There are relatively few examples of restoration prioritization using site-selection algorithms and using principles such as complementarity and cost (Westphalet al. 2003, 2004, Crossman and Bryan, 2006). Quantitative conservation prioritization can identify a network of sites using an algorithm that can reach conservation targets while minimizing cost (Moilanen and Ball, 2009). Prioritization for restoration actions can be done similarly. Marxan is a tool used to design efficiently configured protected area networks or reserve systems and the recently developed Marxan with Zones (Marxan Z) increases the flexibility of this software to include multiple cost and multiple-zones configurations (Watts et al., 2008; Moilanen and Ball, 2009).

1.1 Objectives

To examine the benefits of spatially optimizing restoration actions for conventional seismic lines in northeastern Alberta, I used Marxan Z (Watts et al., 2008a) to identify and prioritize key areas for restoration. Key to prioritizing restoration sites is the consideration of previously identified priority restoration areas for caribou habitat, probability of natural forest regeneration on seismic lines, bitumen pay thickness identifying areas likely to be continually developed and disturbed, linear feature density to identify cost-benefits to caribou and distance to nearest road which provide equipment access for restoration. Zones were as efined active reclamation (active restoration), natural regeneration (passive restoration) and zones available for industrial development. Different scenarios were compared by altering costs and targets to optimize restoration of 50% of all current conventional seismic lines in the study area (total lines = 2545 km, target = 1273 km).

2.0 Methods

2.1 Study Area

The study area totaled 180,603 hectares of boreal forest south of the city of Fort McMurray within the Stoney Mountain area of northeast Alberta (56° 27′ 37″ N, 111° 42′ 14″ W, Fig. 1). The Stoney Mountain area is characterized by having relatively flat terrain, but with a gradual shift in elevation from 246 m to 632 m in the southeast. The area is classified as Central Mixedwood Natural Subregion with a smaller section of the Lower Boreal Highlands Natural

Subregion (Alberta Environment and Sustainable Resource Development, 2005). Vegetation includes black spruce (*Picea mariana* (Mill.) B.S.P) or larch (*Larix laricina* (Du Roi) K. Koch) dominated bogs, poor fens, rich fens and marshes in the lowland where the soil is saturated for all or part of the year (Beckingham and Archibald 1996). On upland sites, soils are well drained with tree cover dominated by aspen (*Populus tremuloides* Michx.), poplar (*Populus balsamifera* L.), jack pine (*Pinus banksiana* Lamb.), white spruce (*Picea glauca* (Moench) Voss) or 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 of 478 mm (Natural Regions Subcommittee, 2006). July is the wettest month, with mean precipitation of 85 mm, while February is the driest month, with mean precipitation of 18 mm (Natural Regions Subcommittee, 2006). The study area is occupied by populations of the threatened woodland caribou (Schneider et al., 2010). Exploration of the Stoney Mountain area for its rich deposits of oil and gas resulted in ~12,000 km of linear disturbances, 4,350 km of which are in our study area with 2,545 km of conventional seismic lines (Nash, 2012).

2.2 Identifying Potential Seismic Lines for Restoration

In order to target prioritization of conventional seismic lines for restoration, lines needed to be mapped and an assessment of their current conditions created. Seismic line data were provided in a lineal inventory by Greenlink Forestry Inc. (2011), which used aerial photographic interpretation using a 3-dimensional software package called "Softcopy" (Lineal Characterization Manual and Specifications, 2012). All linear features greater than 50 m in length were delineated as polylines of linear disturbances and this included roads, pipelines and seismic lines. All seismic lines were terminated when they intersected a pipeline, well site or road and re-started if present on the other side of those features. Heights of vegetation on seismic lines were averaged to the nearest meter and segmented into ≥50 m lengths based on consistency of vegetation height. Only conventional seismic lines with vegetation <3 m in height were included here. Seismic lines having vegetation ≥3 m were assumed to already be on a successional trajectory of recovery (passive restoration) and likely already had woody vegetation, thus not requiring active restoration efforts. The 3 m height used here is also the minimum green-up rule required by forestry regulations for wildlife in Alberta (Forest Practices Code, 2001; Alberta Environment and Sustainable Resource Development, 2012).

This height criterion is applied equally across all forest stand types. In total, 1292 km of seismic lines were analyzed. Seismic lines were divided into “planning units”, each of which can be allocated to a zone in the optimization analysis (Klein et al., 2009). Each planning unit is a 4 x 50 m polygon centered on a segment of seismic line (polyline). Conventional seismic lines vary in length and all lines did not divide equally into 50 m segments. A small number of polygons were less than 50 m in length (i.e. slivers); segments less than 30 m were removed for a total of 29, 348 planning units to be zoned. Total length of seismic line in each planning unit was summarized.

2.3. Restoration Priority Areas for Woodland Caribou

Habitat restoration priority areas (maps) for woodland caribou provide broad guidance for focusing woodland caribou restoration efforts (AESRD, 2013). Mapping of these restoration zones within the study area include the Eggpony and Algar caribou ranges and are based on all available and relevant information sources, including caribou radio collar data. The Federal Recovery Strategy for Woodland Caribou (2012) was referenced when considering which caribou and landscape features to include. Priority areas within caribou ranges were ranked into 5 ordinal categories for restoration ranging from 1 (high) to 4 (low) and 5 (data deficient). Highest valued habitat (1) was quite scarce within the study area (174 m^2) and contained no seismic lines. For purposes of this analysis, three habitat categories described priority caribou restoration: 2^{nd} order, 3^{rd} order, and 4^{th} order (low priority and data deficient). Amount of each habitat category was summarized in each planning unit.

2.3 Optimization Analysis for Restoration

Marxan (Ball and Possingham, 2000; Possingham et al., 2000) is the most commonly used software for reserve planning and has been adapted to include multiple zones. Marxan with Zones (Watt et al., 2008a) was used to allocate planning units to: available, passive restoration and active restoration. Available zones include no restoration; passive restoration zones include sites where development is limited to allow for natural regeneration of seismic lines; and active restoration zones include sites where reclamation should occur (i.e. site preparation, mounding, tree planting).

Marxan with Zones allocates a zoning configuration that attempts to achieve a set of targets while minimizing "cost" (Watt et al., 2008a). To achieve the best option for restoration of conventional seismic lines, four costs were included in the analysis: bitumen pay thickness, linear feature density, natural regeneration probability and distance to nearest road (Fig. 3). Bitumen pay thickness is for the Athabasca Wabiskaw- McMurray deposit and describes the bulk rock volume of a reservoir of oil sands divided by its area (Alberta Energy). Cost is higher for greater pay thickness because the site is more likely to undergo intensive energy development at detriment to restoration efforts, thus cost equates to the actual bitumen pay thickness value. Linear feature density for every 2 x 2 m cell includes the density of all pipelines, roads, seismic lines (2D and 3D) and trails within a 1000 m search radius (m/m^2). Maximum value of linear density for each planning unit was used as the cost. Cost was higher as linear feature density increased because restoring areas with low linear feature density increases the patch sizes of non-fragmented habitat in the study area. There was usually higher linear feature density in areas of high bitumen pay thickness, as these two costs were related. Probability of seismic line regeneration was estimated from a logistic regression model predicting vegetation recovery to 3 m based on whether 50 m plots along lines reached a 3 m height measured from LiDAR data (van Rensen et al., in review). A classification threshold was identified for each seismic line segment when a segment could be considered regenerated to a 3 m height at 10, 30, 50 years post-disturbance. The classification threshold balanced the trade-off between false positives and false negatives by maximizing the kappa statistic (R Package PresenceAbsence; Freeman, 2007). These data were modified into costs for passive and active zones (Table 1). In passive restoration zones, there was low cost for sites predicted to be regenerated to 3 m within 10 years (1), moderate costs for sites regenerating in 30 years (3), high costs for sites regenerating in 50 years (5) and very high costs for sites not regenerated within 50 years (10). In active restoration zones, there was low cost for sites predicted to regenerate between 30-50 years (1), moderate costs for sites regenerating between 10-30 years (3), high costs for sites not regenerating for greater than 50 years (5) and very high costs for sites regenerating in 10 years (10). This cost method represents a "triage" approach for restoration (Noss et al., 2009). Forest regeneration probability was used to represent costs for each zone reflecting restoration priorities. Distance to nearest road was calculated as the minimum log 10 transformed (with a constant of 1) distance (km) to the nearest road for each planning unit. Overall, the available zone had no costs and the passive restoration zone and active restoration zone had bitumen pay thickness, linear feature density, distance to nearest road and the corresponding regeneration probability costs.

Marxan with Zones minimizes the total cost of the zoning plan (C) (Klein et al., 2010):

$$C = \sum_{i=1}^{M} \sum_{j=1}^{N} c_{ij}\, x_{ij}$$

where the cost of placing a particular planning unit ($i = 1, \ldots, M$) into a particular zone ($j = 1, \ldots, N$) is represented by c_{ij} (the total costs for that zone) and $x_{ij} = 1$ if the i^{th} planning unit is included in the j^{th} zone, subject to the constraint that a set of zone-specific targets and a planning unit can only be placed in one zone, such that:

$$\sum_{j=1}^{N} x_{ij} = 1$$

Costs were equally weighted for each zone and scenario.

2.4 Scenarios

Six scenarios with different targets and costs were estimated in Marxan with Zones (Watt et al., 2008a) in order to examine how prioritization for restoration would change if targets and costs differed (Table 2). Scenario 1 targeted 50% of the seismic lines into active or passive restoration zones based on costs that considered only forest regeneration probability. Scenario 2 zoned the same targets as scenario 1, but included bitumen pay thickness and linear feature density as additional costs. Scenario 3 targeted 50% of the seismic lines, 80% of caribou 2nd priority area, 50% of 3rd priority and 25% of 4th priority, with costs for regeneration probability. Scenario 4 included the same targets as 3 (50% seismic lines and caribou), but included costs for bitumen pay thickness and linear feature density in addition to regeneration probability. Scenario 5 targeted 50% of seismic lines for restoration and included costs for regeneration probability and distance to nearest road. Scenario 6 had the same costs as scenario 5, but also included targets for caribou. Distance to nearest road and linear feature densities were not included in the same scenario because they are contradictory. For instance, areas closest to roads, while easier to access for reclamation, are typically areas of highest linear feature density and in locations of highest bitumen pay thickness.

Marxan with Zones uses simulated annealing to find the near-optimal zone configuration that both minimizes the sum of planning units and zone boundary costs (Watts et al., 2008a; Klein et al., 2010). To control the level of clustering of zones for solutions, a "zone boundary cost" can be adjusted to minimize the boundaries between zones relative to planning unit cost (Watts et al., 2008a,b). To preserve local scale variation in forest regeneration probability across the landscape the zone boundary cost was set to 0. Iteration number was chosen through adaptive calibration described in Watts et al. (2008b); 200 iterations were sufficient for each scenario (i.e. greater iterations resulted in limited dissimilarity in zone selection). The best solution was mapped for the active and passive restoration zones and the planning unit selection frequency for scenario 4. Finally, total reclamation costs for the best solutions for each scenario were compared.

3.0 Results

Zonation for active and passive restoration revealed high local variation in regeneration probability across the landscape regardless of scenario used. There were, however, consistently more active restoration zones than passive restoration zones selected (Fig. 3-4). In scenario 1, which only included costs for regeneration probability, targets were met (50% restoration of seismic lines) and the number of planning units selected in the best solutions for active and passive restoration were 9304 and 5345, respectively (Table 3-3, Fig. 3-4). Compared to other scenarios, scenario 1 had the highest selection of planning units zoned for passive restoration. In scenario 2, when costs for bitumen and linear feature density were included in addition to regeneration potential, restoration targets were not met and only 39% of seismic lines were zoned for restoration. While the amount of planning units selected for active restoration (9228 PUs) was similar to scenario 1 (9304 PUs), there were approximately half (2125 PUs) the amount zoned for passive restoration in scenario 2 than scenario 1 (5345 PUs; Table 3-3, Fig.3-4). Including costs for bitumen and linear feature density forced the solution away from areas ideal for passive restoration (i.e. natural regeneration). In scenario 3 that included caribou, but no costs for bitumen pay thickness or linear feature density, targets were met for seismic lines and caribou priority restoration habitat. Compared to scenario 1, which did not include caribou targets, there were a greater number of active restoration zones (9673 PUs) and fewer (4966 PUs) passive restoration zones (Table 3-3, Fig.3-4). Scenario 4, which included caribou and costs for bitumen pay thickness and linear feature density, did not meet targets for seismic lines, zoning only 40% of lines for restoration, but did meet all caribou targets. This scenario was similar to the best solution for scenario 2; including caribou restoration priority areas did not alter the zonation substantially with 9444 active and 2197 passive restoration planning units (Table 3-3, Fig.3-4). Costs for distance to the nearest road (i.e. accessibility for reclamation) were included for scenarios 5 and 6. In scenario 5, which did not have targets for caribou, the best solution focused restoration sites near highway 63 and 881, meeting, and exceeding, targets for 50% of seismic lines zoned for restoration. Scenario 5 zoned the greatest number of planning units for active (10500 PUs) (Table 3-3, Fig. 3-4). When adding caribou targets representing scenario 6, all targets were met, although there was a reduction in active zones (9964 PUs) and an increase in passive zones (4650 PUs) (Table 3-3, Fig. 3-4), as restoration zones were forced further west towards high priority caribou restoration zones.

Selection frequency of planning units for active and passive zonation in scenario 4, which included caribou targets, bitumen pay thickness and linear feature density revealed frequent selection for active zonation in planning units away from areas of high industrial development and within high priority caribou areas (Fig. 3-5). There were fewer planning units consistently selected for passive restoration (i.e. selection frequency in the 181-200 runs; red in Fig. 3-5). A large number of planning units were never selected for either active or passive restoration zones (i.e. 0-20 times; blue in Fig.3-5); while a number of planning units were equally selected for passive or active restoration (Fig. 3-5).

Total cost to actively reclaim all conventional seismic lines <3 m in vegetation height assuming an average cost of $3,776/km (Tim Vinge, personal comm.) was estimated at $4, 877,455.80 CAD. To restore 50% of the seismic lines without zonation would cost $2,770,451 and achieve less conservation value for woodland caribou. Using the best solution from Marxan with Zones and only considering regeneration probability (scenario 1) the cost to restore 50% of seismic lines was estimated at $1,756,595 (Table 3-4), a savings of $1,013,856.

When additional costs for bitumen pay thickness and linear feature density (scenario 2) were included it resulted in a cost savings of $401,200 to restore 39% (50% target not reached) of the 2D seismic lines (Table 3-4). Incorporating costs for regeneration and targets for caribou habitat (scenario 3) results in a cost savings of $944,189 for restoration of 50% of seismic lines. Including costs for regeneration, bitumen pay thickness and linear feature density, and including targets for priority restoration caribou habitat (scenario 4), saves $414,794 for 40% (50% target not reached) of seismic lines restored. Considering the best solutions for scenarios 5, which included costs for distance to road and regeneration probability, and scenario 6, which also targets caribou restoration areas, the total savings to restore 50% of the seismic lines was estimated at $788,051 and $889,248, respectively (Fig. 3-6).

4.0 Discussion

Zoning seismic lines for restoration incorporated fine scale variation in regeneration patterns and large scale variation in industrial development and road access. This could result in substantial reclamation savings, while at the same time, reducing forest fragmentation in important woodland caribou habitat and decreasing the likelihood of line re-disturbance disrupting restoration activities. While past studies have optimized restoration of degraded habitats (Crossman and Bryan, 2006, Thomson et al., 2009, Langhans et al., 2014,Yoshioka et al., 2014), this analysis is one of the first to effectively account for forest regeneration probability on seismic lines and economic costs to optimize restoration to benefit woodland caribou in the boreal forest. Generally, active restoration (i.e. reclamation) was recommended for re-vegetating more of the land base than passive restoration (i.e. natural regeneration). A number of lowland habitats with slow regeneration (i.e. fens and bogs) forced zoning for active restoration (i.e. reclamation) or even no restoration rather than passive restoration.

The best solution for scenario 1 reflects the optimal sites to restore 50% of the total 2D seismic lines < 3 m in height based on regeneration probabilities alone. Without including economic costs (i.e. areas of high industrial development), restoration savings could exceed ~$1 million CAD, requiring 465 km of seismic lines to be actively reclaimed and 267 km to be designated for passive restoration. This scenario selects more areas for passive restoration (natural regeneration) than the other scenarios. Passive restoration zones appear to concentrate in upland areas that are predicted to regenerate naturally to 3 m within 30 years following linear disturbance (van Rensen et al., in review). Even though caribou restoration priority area targets were added, scenario 3 has near identical patterns to scenario 1, with the exception of a few hundred planning units changed to active instead of passive restoration zones. Zones were shifted primarily to the 2nd priority restoration caribou habitat, which has the most stringent target of 80% of the lines restored, compared to lower priority areas (50% and 25%). Woodland caribou select for peatland complexes (bogs and fens) to avoid co-habiting areas with moose and deer (i.e. apparent competition) (Seip, 1992; Bradshaw et al., 1995; Stuart-Smith, A.K., 1997). Seismic lines in these areas are likely to experience lower regeneration probabilities, particularly if there is an elevated water table (van Rensen et al., in review). The large number of planning units zoned for active restoration in the solution and large proportion of lowland habitat in the region suggests that to benefit woodland caribou through habitat restoration, peatland reclamation techniques will be key (van Rensen et al., in review).

The addition of economic costs into scenarios 2 (no caribou) and 4 (caribou) altered the zonation patterns. Bitumen pay thickness and linear feature density had a strong influence on the selection of restoration zones. Restoration targeted areas in the southeast portion of the study region that had, and continue to experience, high oil sands development. Additional economic costs combined with high regeneration costs (areas predicted to have low regeneration 50 years post-disturbance) resulted in a failure to meet the targeted 50% of seismic lines zoned for restoration. Only ~40% of planning units were zoned for restoration (~570 km of lines), with the majority targeted for active restoration (~460 km). These two scenarios had similar outcomes with the addition of caribou targets hardly altering the best solution. The highest priority restoration areas for caribou, within the boundaries of the Algar and Eggpony caribou herds, are in the western part of the study area, and did not overlap with the areas of highest bitumen pay depth where future re-disturbance is likely. The 4th priority caribou restoration area targets only 25% of the seismic footprint to be restored, which was achievable without overlapping the highest development areas.

In scenarios 5 and 6, distance to the nearest road was included as a cost in addition to regeneration probability. In scenario 5, solutions selected restoration zones primarily around Highway 63 and Highway 88, which run along the southeastern and eastern border of the study area. There was high variation in active and passive restoration zones within these areas.

When caribou targets were included, more restoration zones were selected in the western part of the study site in the 2nd and 3rd priority restoration areas, although the pattern between passive and active regeneration did not change dramatically. Access into much of the region, particularly in summer, is limited because of the large number of wetlands (including fens) that are frequently flooded. Reclaiming lines with improved accessibility would increase the feasibility of reclamation activities, but would reduce benefits to woodland caribou. Caribou prefer undisturbed intact forest (James and Stuart Smith, 2000), which would be further from existing roads and high densities of industrial activity. Seismic lines closer to roads may be more susceptible to re-use by all-terrain vehicles, which could inhibit reclamation or natural regeneration through soil compaction if restricted access management is not enforced (Lee and Boutin, 2006). Dollar costs for active and passive restoration did not include the potential costs for access management and enforcement during re-vegetation lag times, thus cost savings could be underestimates.

Selection frequency of zones indicates the "irreplaceability" of particular planning units in reaching conservation and restoration targets. Irreplaceability is how important the inclusion of a planning unit is in a network of priority areas to meet targets effectively (Wilson et al., 2009). Sites selected for either passive or active restoration in close to 100% of the 200 iterations should be those first prioritized for restoration dependent on available budget. For this analysis, the selection frequency for active and passive restoration zones for scenario 4, which included caribou priority restoration targets and costs for bitumen pay thickness and linear feature density, would be most beneficial for woodland caribou conservation. There were few areas consistently selected for passive restoration compared to active restoration (Fig. 5). Areas of seismic lines consistently selected for active restoration should be prioritized for treatment first.

Realistically, decision makers have to consider multiple solutions for restoration planning of seismic lines. Planning units used here were 50 m segments of line, but for practical reasons operators may prefer to treat a longer stretch of seismic line (i.e. 1 km) with either active or passive restoration. However, there can be substantial variation in vegetation along such lengths. Planners could look for sections of lines that contain a majority of planning units in one zone to decide upon treatments for restoration. Additionally, industry stakeholders would have knowledge about which lines are eligible for restoration and preferred access points to allow for equipment and operators to effectively reach line for treatment application. This information could be included in future optimizations as potential cost surfaces.

To account for further ecological, economic and social restraints in restoration planning, additional focal species and industrial costs specific to the region could be considered. For example, species or habitats important for hunting or the consideration of forest management areas could have been included as additional features or costs. Despite the limited number of conservation features in this study, threatened woodland caribou are currently the main driver of conservation and restoration planning by industry and provincial and federal governments in the boreal forest of northeastern Alberta. This suggests that funds for restoration would be allocated to projects benefiting caribou. Habib et al. (2013) used MARXAN to investigate flexible biodiversity offset systems to target woodland caribou in Alberta. Spatial configurations for seismic line re-vegetation from this analysis could support the selection of conservation offsets, particularly when evaluating economic costs.

Solutions in this analysis are a first step at identifying 2D seismic lines for restoration. Environmental stochasticity (i.e. fire, insect outbreak, floods and drought) would require adaptation necessitating an active portfolio for restoration planning. For example, fire is prevalent in the area and there is a high risk of fire disrupting restoration applications at the site level. Frameworks for addressing issues such as restoration scheduling are outlined in studies that emphasize the importance of clear objectives and structured analyses for prioritization, whichever optimization software is used (i.e. Zonation, Marxan; Thomson et al., 2009; Wilson et al., 2011). Restoration of seismic lines is likely to be implemented incrementally, not at once, and restoration scheduling for seismic lines would be beneficial. Optimization would be improved by considering lag times of re-vegetation after linear disturbance and the success rate of different reclamation treatments. It is unlikely that all restoration treatments result in 100% success in terms of reaching 3 m height, and without estimates of restoration efficacy, it is difficult to project the timing of successful restoration. Using Marxan with Zones for optimization can allow for adaptation and improvement of solutions as more information becomes available or as lines are considered restored. Successfully restoring seismic lines will inevitably require the cooperation of a number of stakeholders such as forestry, energy, land owners and government. The real value of this work is that it exemplifies a methodology to quantitatively optimize restoration planning that landscape managers can apply to improve restoration at a strategic level, while accounting for constraints they believe important for consideration.

4.1 Conclusion

Optimization methods can be used to prioritize sites for restoration and differentiate among zones, such as active or passive restoration. In this study, a quantitative method for prioritizing restoration that improves defensibility of decision making is examined compared to ad hoc methods typically used to determine current restoration efforts. Substantial cost savings, here up to $1 million CAD based on conservative reclamation costs, can also be achieved by considering regeneration probabilities when selecting for active and passive restoration. More cost effective restoration actions will provide funding resources for other reclamation and conservation projects. Marxan with Zones (Watts 2008a) can be a useful approach for quantitatively selecting 2D seismic lines for restoration.

Tables 3-1; 3-2; 3-3

Table 3-1
Cost for regeneration probability for passive and active restoration zones. Costs are dependent on time to reach an average 3 m of vegetation on a seismic line.

Zone	Regeneration Cost			
	<30 years	30-50 years	50-70 years	>70 years
Passive	1	3	5	10
Active	10	3	1	5

Table 3-2
Description of scenarios with different targets and costs. Costs for bitumen pay thickness, linear density (m/m^2) and distance to nearest road (log10 +1) represent the actual values of each. * indicates inclusion.

Scenario	Abbr.	Targets				Costs			
		Caribou priority %			Lines %	Bitumen Pay Thickness	Linear Density	Distance to Nearest Road	Regeneration Probability
		2	3	4					
1	S1c0b0r0	0	0	0	50				*
2	S2c0b1r0	0	0	0	50	*	*		*
3	S3c1b0r0	80	50	25	50				*
4	S4c1b1r0	80	50	25	50	*	*		*
5	S5c0b0r1	0	0	0	50			*	*
6	S6c1b0r1	80	50	25	50			*	*

Table 3-3
Planning unit assignment to active restoration, passive restoration and available zones in the best solution for each scenario after 200 iterations in MarxanZ.

Scenario	Planning units assigned to zones (#)			Targets Met	
	Active	Passive	Available	Caribou %	50% Seismic Lines
1	9304	5345	14699	NA	Yes
2	9228	2125	17995	NA	No
3	9673	4966	14709	Yes	Yes
4	9444	2197	17707	Yes	No
5	10500	4106	14742	NA	Yes
6	9964	4650	14734	Yes	Yes

Figures 3-2; 3-3; 3-4; 3-5; 3-6

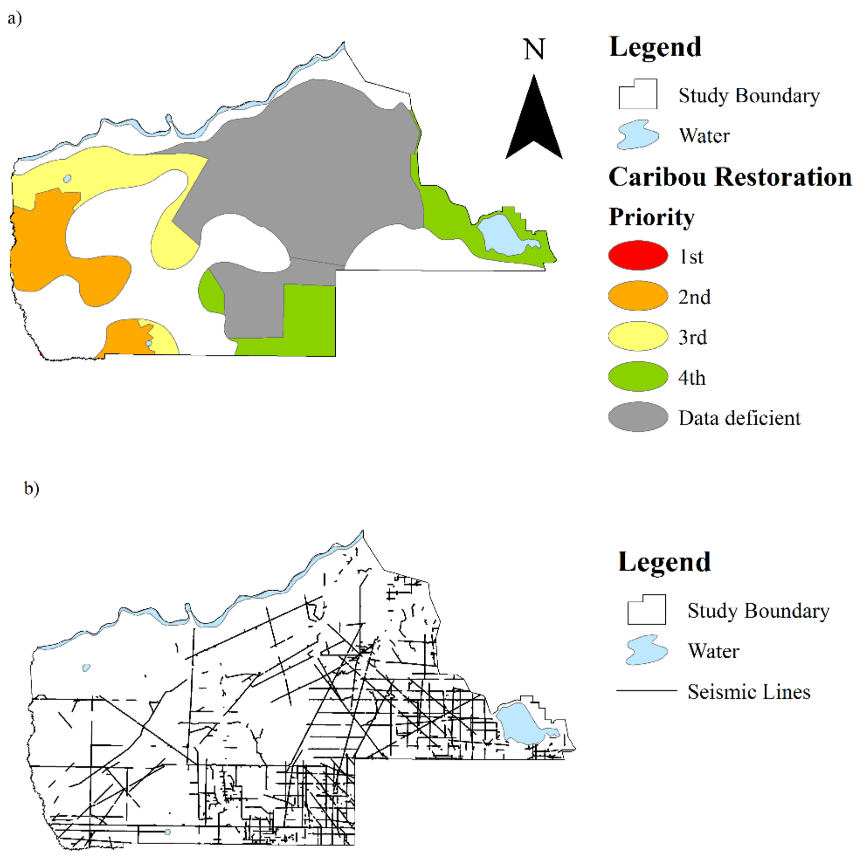

Fig. 3-2. Restoration features. (a) Caribou priority restoration areas (ESRD). 1st priority caribou restoration habitat is a minute portion of the study area in the bottom southwest corner and is not affected by 2D seismic lines. (b) 2D seismic lines over 3 m in average height determined by Greenlink Forestry Inc. lineal inventory (2012).

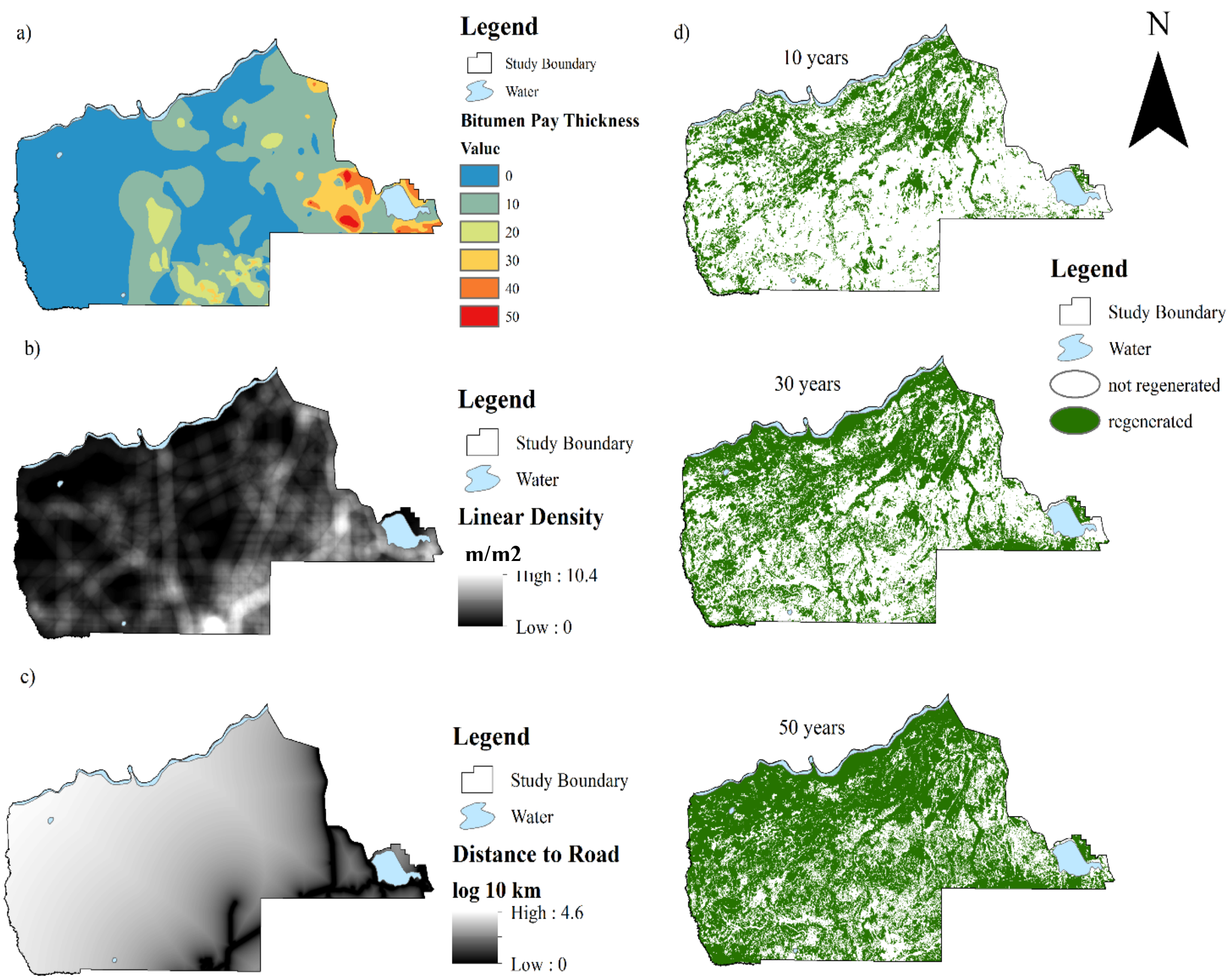

Fig. 3-3. Costs input into Marxan with Zones scenario runs. (a) Bitumen pay thickness (Department of Energy). The higher the cost for restoration the higher the bitumen pay thickness. (b) Linear feature density in m/m^2 from Greenlink Forestry Inc. lineal inventory (2012). Cost for restoration increases with increasing linear feature density (c) The distance to the nearest road (log 10 transformed). Cost for restoration increases with decreasing distance to the nearest road. (d) Probability of regeneration to an average 3 m vegetation height 10, 30 and 50 years post-disturbance classified into regenerated (green) and non-regenerated (white) using an optimal classification threshold (maximum kappa).

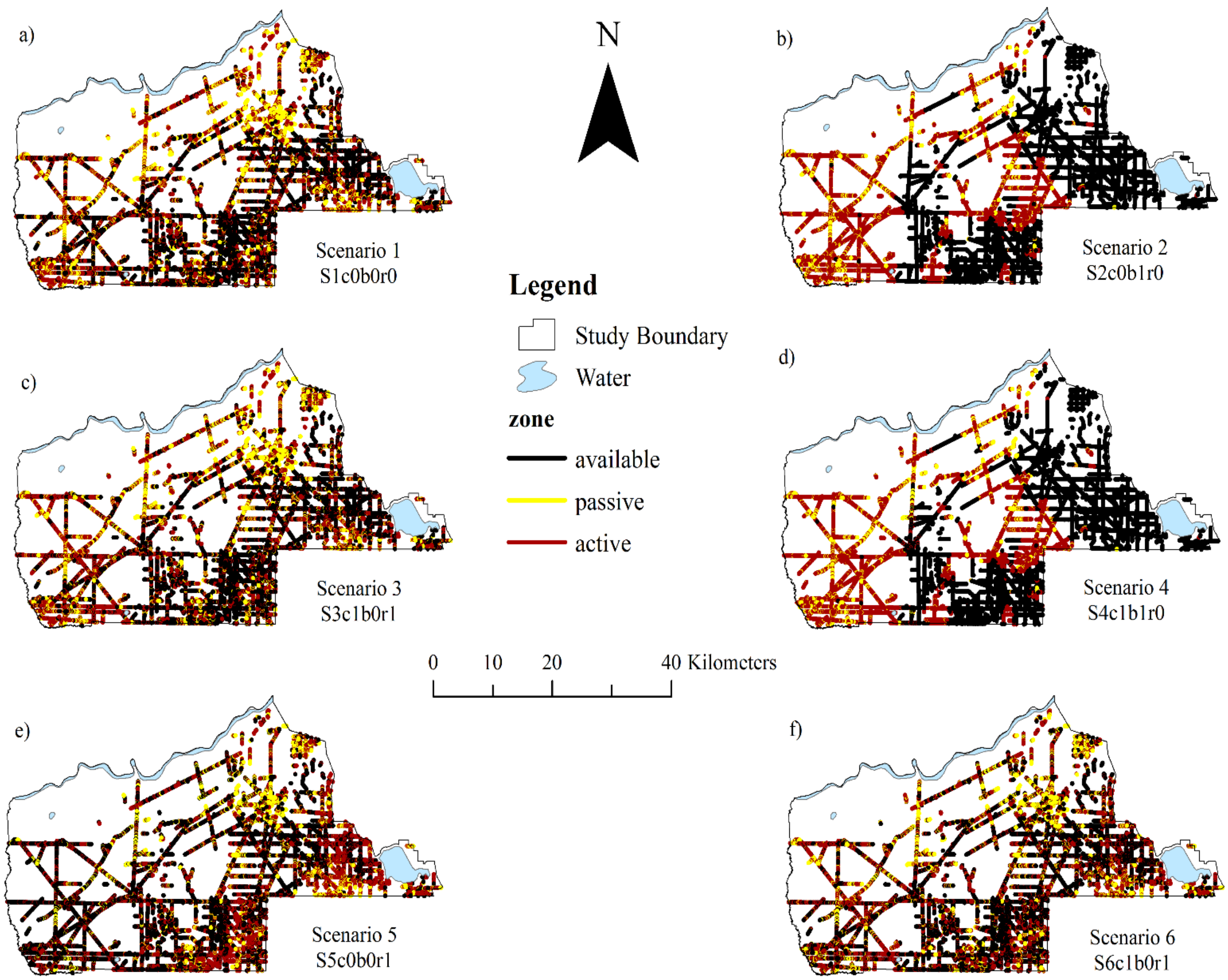

Fig. 3-4. Best solution from Marxan with Zones scenario runs. Planning units were zoned for available (black), passive restoration (yellow) and active restoration (red) for 6 scenarios. All scenarios targeted the restoration of 50% of 2D seismic lines that were less than 3 m height of vegetation. (a) S1c0b0r0 only included costs for regeneration probability. (b) S2c0b1r0 included costs for regeneration probability, bitumen pay thickness and linear feature density lineal inventory. (c) S3c1b0r0 includes costs for regeneration probability and targets for priority restoration areas for caribou. (d) S4c1b1r0 includes costs for regeneration probability, bitumen pay thickness, linear feature density and targets for priority restoration areas for caribou. (e) S5c0b0r1 includes costs for regeneration probability and distance to nearest road. (f) S6c1b0r1 includes costs for regeneration probability and distance to nearest road and targets for priority

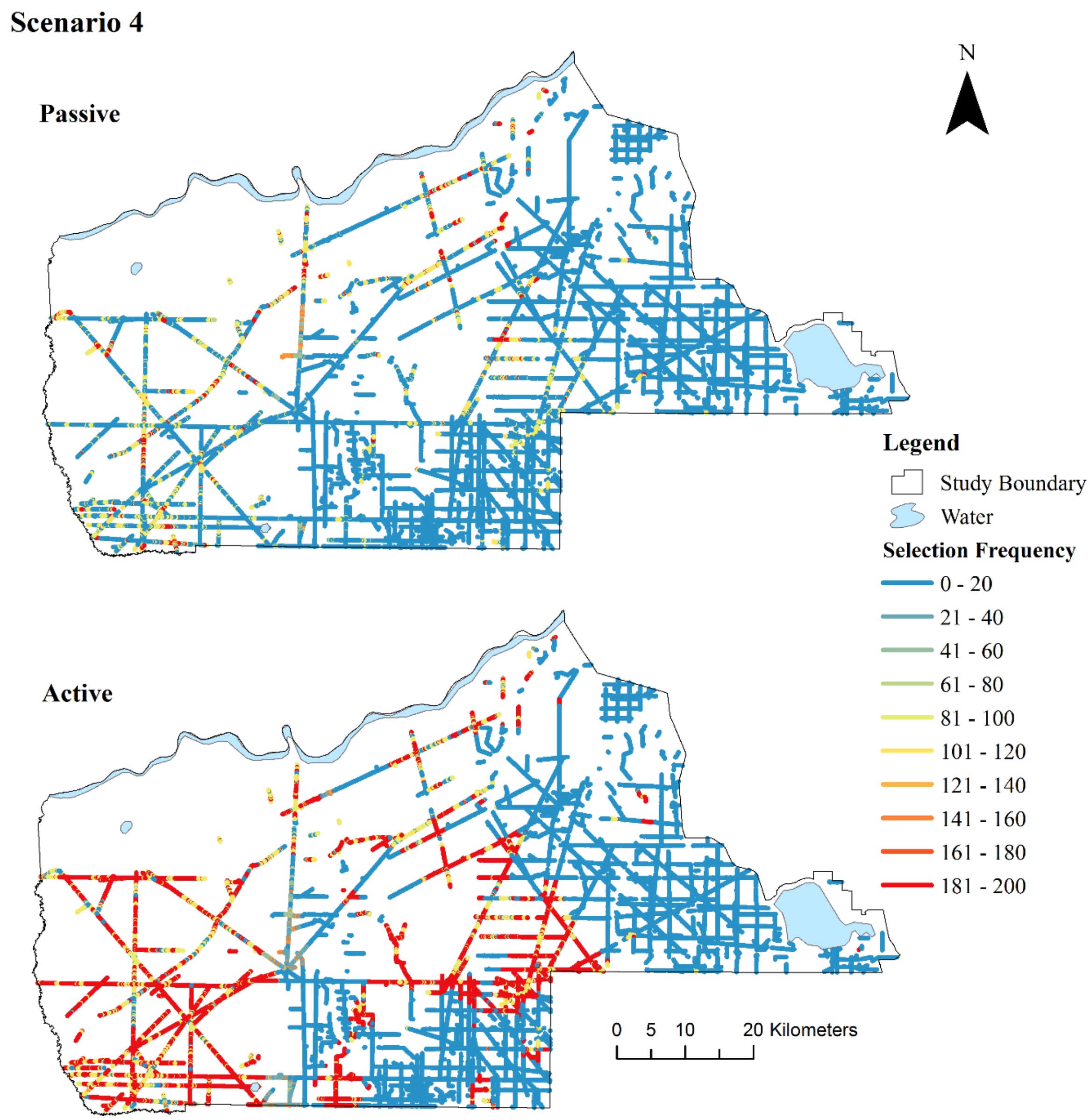

Fig. 3-5. Selection frequency of scenario 4 (S4c1b1r0) run for 200 iterations in Marxan with Zones for passive restoration zones (top) and active restoration zones (bottom). 40% of seismic lines were zoned for restoration. Planning units in blue were selected less frequently than planning units in orange or red.

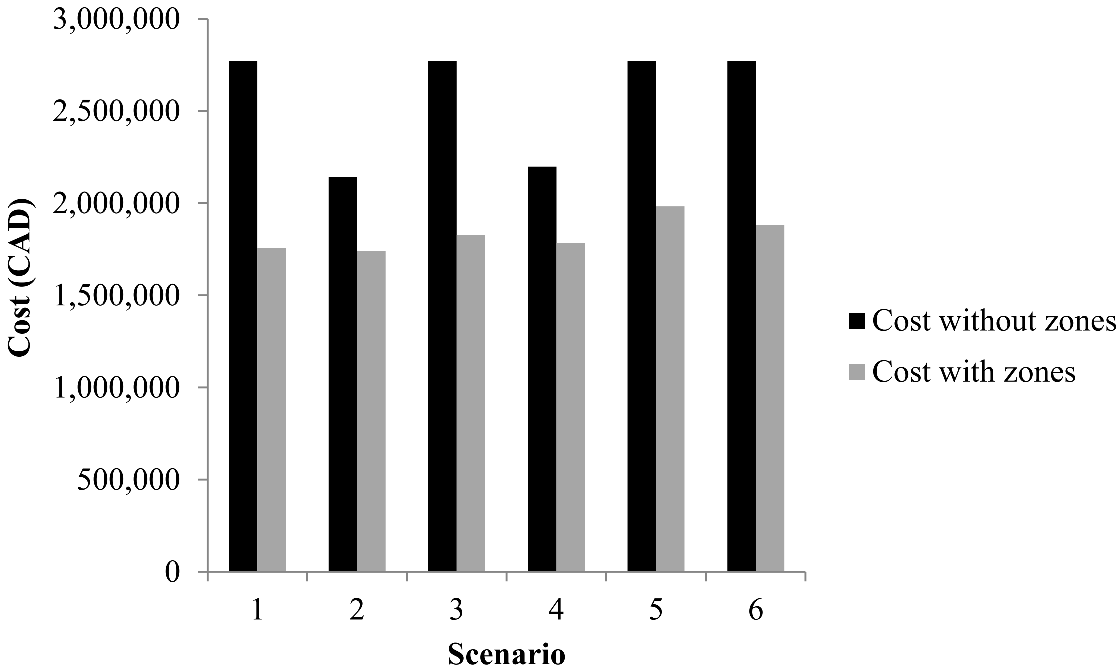

Fig. 3-6. Cost in Canadian dollars with and without zones for scenarios 1-6 from Marxan with Zones best solutions. Average cost of reclaiming a seismic line is $3776/km. Note that scenario 2 and 4 did not reach the targeted 50% of seismic lines zoned for restoration (39% and 40%, respectively).

Chapter 4: General Conclusion

4.1 Summary and implications of predictive modelling of seismic line regeneration

Models that inform and predict biological processes can improve conservation planning and management decisions. A biological process can be defined as a series of events whereby species interact with each other and the landscape (Johnston et al., 2013). Just as models can lead to improved decision making, they can simultaneously provide insight into biological processes underlying their development, identifying what we know and what we want to learn. The biological process examined in this thesis was the regeneration, or succession, of trees after linear disturbance from 2D seismic exploration. High density of seismic lines, resulting from a wealth of energy resources in northeastern Alberta and energy demand globally, has been found to impact the biodiversity, ecological processes and ecological structure of the northern Boreal forest. To better understand succession on seismic lines, as opposed to disturbances from fire or forest harvest (Revel et al., 1984), I modelled regeneration of vegetation on 2D seismic lines using LiDAR, forest inventories, and Wet Areas Mapping. My results confirmed that regeneration post-disturbance was faster in upland than lowland sites (Revel et al., 1984; Lee and Boutin, 2006; Bayne et al., 2011), but additionally demonstrated the impactful role of terrain wetness and ecosite in determining regeneration potential (Chapter 2). Most likely, fens are fundamentally altered after clearing for 2D seismic, and these habitats are going to be a major challenge for future restoration. Line width and distance to roads were also had strong influence on regeneration patterns, implying that past machinery to clear lines, in combination with re-disturbance from human access, is detrimental to regeneration of these linear disturbances.

LiDAR data has been acquired for more of Alberta than any other province in Canada (pers. com. Barry White). Use of an extensive dataset like LiDAR can help address landscape and local scale questions relevant to ecological issues in Alberta, particularly for remote areas where field sampling may be challenging. I demonstrated a novel methodology, which uses LiDAR data and derived products (i.e. Wet Areas Mapping, Canopy Height Model) to gain a better understanding of the complex ecological process occurring over a diverse array of environmental conditions representing much of Alberta's and Canada's Boreal forest. 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. Maps can also provide information about where areas of slow recovery may overlap with ecologically significant areas, drawing attention to sites of particular concern. As exemplified in chapter 3, regeneration probability maps can also be directly used in restoration planning, providing inputs into optimization software, such as Marxan with Zones (Watts et al., 2008a).

4.2 Summary and implications of spatial restoration optimization

Ecological restoration is “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” (SER, 2004). Most often, restoration priorities are based on expert opinion and generic design criteria using ranking or scoring (Noss et al., 2009). Quantitative methods for prioritizing restoration efforts can provide decision support tools for landscape management, which are more transparent and scientifically defensible. It is critical in restoration planning that an understanding of the relevant ecological processes on a landscape underlies the planning process (Davis, 2013). Restoration of seismic lines in northeastern Alberta had been identified as important for maintaining biodiversity in the Boreal forest, with particular attention to woodland caribou, listed as “threatened” under the federal Species at Risk Act (SARA). In chapter 3, I explicitly incorporate regeneration modelling results from chapter 2 to create optimal configurations of sites zoned for either active restoration (reclamation), passive restoration (natural regeneration) and available for development. The array of scenarios presented show that it is possible to benefit East Side Athabasca Caribou herds by shifting restoration of seismic lines away from areas of high development (i.e. high bitumen pay thickness and linear density), but substantial reclamation will be required. Again, this work strongly supports the need to develop reclamation techniques for peatlands, which are prevalent specifically within caribou habitat. Chapter 3 focused on woodland caribou, but this sensitive species may act as an umbrella for other forest species experiencing pressure from oil sands development. A carefully laid out restoration plan can have benefits beyond those to caribou, and potentially increase the overall resilience of Boreal forest habitats in the region.

Seismic lines that were predicted to regenerate the slowest (i.e. wet fens), may have been too costly to be zoned for restoration in the study area. The optimization methods for restoration planning here were designed to target sites that were moderately "degraded," from regeneration probabilities, thus following a triage approach. Triage when selecting sites for restoration could result in spatially and functionally disconnected habitats (Noss et al., 2009). If further research on fen reclamation is not conducted and applied, we risk the decline of these valuable peatland ecosystems in the long term due to their slow recovery rates. The avoidance of sites exceptionally slow to regenerate should be cautioned as a limitation of the spatial restoration configurations within the study.

4.3 Landscape management in Alberta

Recently, the Alberta Government has strived to use an integrated landscape management approach to developments by attempting to understand the cumulative effects on the environment instead of a case-by-case management approach (Government of Alberta, 2008). Part of this response was the development of the Land-Use Frameworks, the first of which is the Lower Athabasca Region Plan (LARP; Government of Alberta, 2012). The LARP plan aims to support biodiversity through a Biodiversity Management Framework, which is currently under development (Government of Alberta, 2012). The Biodiversity Management Framework will include thresholds for biodiversity that will initiate a management response, which can involve reclamation to reduce the amount of human footprint on the landscape. While new footprint is being added rapidly in the Lower Athabasca Region, the aging linear footprint, particularly 2D seismic, is still contributing to the total area and density of disturbances. The work presented in chapter 2 and 3, in combination, can be used to support decisions in the context of landscape management and reclamation planning within one of the busiest areas of the Lower Athabasca Region. If biodiversity thresholds are triggered, management actions may be required by government or industry. Understanding where to provide the most beneficial and cost-effective restoration at a landscape scale helps manage cumulative effects by avoiding the continual triggering biodiversity thresholds.

As 2D seismic lines are a legacy disturbance, the responsibility to restore these lines will require the co-operation of numerous stakeholders if continued development is limited by disturbance thresholds. The Cumulative Environmental Management Association (CEMA) is the leading multi-stakeholder group in the Regional Municipality of Wood Buffalo, and is based in Fort McMurray. As a representative of diverse stakeholder groups, CEMA is in a position to use the results of this research on seismic line regeneration patterns and spatial restoration planning (optimization) to make recommendations to provincial and federal governments on the cumulative impact of oil sands development the Stoney Mountain area. The slow regeneration of vegetation on seismic lines in certain habitats (i.e. upwards of 50 years) should be a signal that best practices and improved technology for future exploration is needed, despite their higher costs. As much of the Athabasca oil sands have been mapped, improved data sharing agreements are also needed by industry to help alleviate the need for additional seismic exploration. Repeated seismic line exploration (4D) will continue, but minimizing overall disturbances can be achieved through sharing data and planning.

4.4 Future research

This study looked at two criteria for forest regeneration on seismic lines: vegetation reaching a 3 m height and vegetation reaching 50% of the adjacent stand height. These two criteria allow for a relative comparison of growth across the different stand types and topography found in the Stoney Mountain Area of the Boreal forest. Generally, these criteria provide a simple metric for understanding regeneration patterns on seismic lines. I suspect that as research about the specific structural and compositional requirements of target boreal species increases in availability, it will be increasingly important to accommodate these changes in criteria for restoration planning to suit the needs for a specific target species. This research is limited to height of vegetation on seismic lines, but advances in remote sensing technology, including LiDAR data, can provide information on forest structure and canopy density. Using a combination of both LiDAR data and high resolution satellite imagery, we can increase detail on both structure and composition helping stimulate future research.

Illustrating the variation of regeneration potential across the study area, it follows that the next step would be to develop and test specific reclamation techniques suitable to unique sites. Reclamation techniques with the best possible chance of successfully enabling a desired successional trajectory will reduce overall costs and the need for repetitive reclamation treatments over time. As LiDAR data has extensive coverage, and Wet Areas Mapping continues to increase for regions of the province, the methodology developed in this thesis can be applied to other areas of Alberta. The Alberta Government is working towards a provincial dataset of human footprint, and having a linear inventory of seismic lines is a first step towards modelling their regeneration using LiDAR.

4.5 Final conclusion

Maintenance of biodiversity must exist alongside exploitation, not instead of it; the protection of biodiversity should be integrated into natural resource management (Margules and Sarkar, 2007). For effective decisions about land use and natural resource management, it is important to understand the projected timelines for forest regeneration to make the best decisions about reclamation, including how, where and when. The decisions made today about restoration and management of cumulative effects in Alberta will have impacts on biodiversity over the next 50 years and beyond. Modelling and mapping the regeneration of 2D seismic lines, and demonstrating where restoration will be most challenging, can contribute to significant decisions about the future of oil sands development and the maintenance of biodiversity in northeastern Alberta.

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