DECADAL ASSESSMENT OF SUCCESSIONAL DEVELOPMENT ON RECLAIMED UPLAND BOREAL WELL SITES

by

Laurie Anne Frerichs

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

LAND RECLAMATION AND REMEDIATION

Department of Renewable Resources

University of Alberta

ABSTRACT

Reclaiming previously forested oil sands exploration well sites in northern Alberta is an on-going challenge for the oil and gas industry. Thirty-three experimental sites were constructed and reclaimed between 2004 and 2006 in northeastern Alberta. Our goal was to determine what factors or combination of factors in construction, storage and reclamation phases of development may deter or promote successional development toward pre-disturbance site conditions. Treatments included low (no soil disturbance) and varying degrees of higher disturbance via soil excavation and storage, woody material application and tree planting during reclamation. Survival and growth of planted *Picea glauca* (Moench) Voss (white spruce) were compared between treatments. Soil chemical and physical properties were compared between treatments, and between treatments and forest controls. Naturally regenerating trees and plant communities were compared between treatments, forest controls and cutblocks harvested in 2004. Statistical methods included ANOVA, orthogonal contrasts, ordination analyses using non-metric dimensional scaling and indicator species analysis. Disturbance intensity of treatments and treatment combinations in this study can be characterized and categorized by their degree of impact to aspen regeneration density, similarity in species composition to forest controls and physical similarity of vegetation regrowth to cutblocks, including development of the tree canopy relative to the grass and shrub understory.

Little difference was found in survival and growth of planted spruce, although response was better where soil mixing had occurred. Aspen regeneration density decreased with increasing soil disturbance. Low disturbance methods that used whole slash as a reclamation tool resulted in similar plant species composition to forest controls, and similarity of plant community characteristics to cutblocks including aspen regeneration density. Low disturbance construction that left mulch covering the soil surface altered plant communities by reducing aspen regeneration, deterring forb regeneration, and was prone to invasion by non-native plant

species. Mulch retention resulted in greater spruce and *Populus balsamifera* L (balsam poplar) densities and lower *Betula papyrifera* Marshall (paper birch) density relative to low disturbance sites with whole slash.

High forest soil disturbance resulted in greater alteration of plant communities, further reduced aspen regeneration density, and had high competitive grass and shrub cover which may prevent successful forest reestablishment. Species diversity and tree regeneration density were increasingly reduced by soil surface area exposure during storage. High soil exposure during storage favoured desiccation tolerant species. Duff stripping and root salvage resulted in higher aspen cover and greater similarity to forest controls relative to two-pass stripping. Duff stripped areas had greater grass cover, less tree cover relative to grass and shrubs, and lower plant species diversity than other treatments. Root salvage resulted in highest plant species diversity, and greater similarity to forest controls relative to all but the duff stripping treatment.

Windrowing rather than spreading of whole slash where soil surface area had greater exposure during storage increased aspen and poplar regeneration density. Total cover of spruce and birch was greater in windrowed slash with two-pass stripping than spread slash. Planting trees increased tree cover relative to that of grass and shrubs and plant species richness and/or diversity in low and high disturbance treatments. *Calamagrostis canadensis* (Michx) P Beauv (blue joint), *Rubus idaeus* L (red raspberry) and *Salix* sp. (willow) had higher cover in non-planted treatments.

Sites constructed with low disturbance and treated with whole slash had greatest likelihood of prompt return to typical boreal forest communities and therefore are the preferred construction method for ecological recovery. However, root salvage may be preferable where excavation is deemed necessary for site construction.

ACKNOWLEDGEMENTS

I pursued this project because the boreal forest was (and still is) a fascinating and mysterious place to me. I love the austere beauty of the dank and murky mires, scraggly swamps and foreboding dark forests. And in between these places, the lush cathedrals; some rooms adorned with carpets of moss or lichen, others with gardens of berries, fern groves and never ending green. For plant enthusiasts like myself, there are endless surprises, big and small. I am so very grateful to have had the opportunity to travel to so many sites, and through all kinds of landscapes to experience part of the boreal forest. For this, I thank Dr Terry Osko who entrusted me with his project, and procured excellent vehicles for travel to, and use, in the field.

I came to this project because of a deep concern for Alberta's boreal forest, and with some pessimism regarding the impacts of industrial activities. My outlook has changed somewhat, knowing that along with recommendations previously made, the results of our research provide practical methods for adoption by any company that wants to simultaneously reduce environmental impacts and construction costs. I thank my supervisors, Dr Terry Osko, Dr Edward Bork and Dr M Anne Naeth for their wisdom and support, encouragement and patience, and Dr Glen Armstrong for acting as external examiner. This project turned out to be much more work than I (and perhaps we?) had anticipated. Special thanks to Sarah Wilkinson and Christie Nohos for research and administrative support, and Maggie Glasgow for her continued interest in, and discussions about, the project.

This project would not have been possible without continued support of ConocoPhillips and Nexen, including accommodation and environmental management. From Nexen this includes Rochelle Harding, Randy Slater, Nadine Ford, David Linsley, and Rollo; from ConocoPhillips, Robert Albright, Amelia Smith and Ron Ouellette who provided superb field support and general demonstration of excellence in land stewardship.

I especially want to thank Jeff Pratt, and Nick, Isaac and Cassie; things have sometimes been a little upside down in our home while I have been in school. I appreciate your patience, and giving me space when I needed it. To my Mom and Dad, Ron and Marnie Frerichs, thank you for your support and encouragement through all my life pursuits, and my sister Tracey Frerichs who gets all my jokes, especially the ones that are really not funny at all. Heartfelt thanks to Kim and Craig Pratt, whose support and friendship has meant a lot to me over the past few years. To my friends at SMOG, thank you for helping restore my sanity from week to week, along with friends Karen, Amy, Jackie and Krista. I love you all.

Last but certainly not least, special thanks to Antje (Hulk Wunderkind) Böhm who made that first field season a lot easier than if I had to manage it myself, and Claire (Princess of the Pulaski) Kisko; I have many treasured memories of our experiences in the field, and appreciate your hard work and sense of humour, especially on those long trips, and stretches of days where weather conditions, the insect world and/or the entire Regional Municipality of Wood Buffalo Bear community seemed to be conspiring against us.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I: INTRODUCTION

1. INTRODUCTION

The project, Removing the Wellsite Footprint, was initiated in 2003 to address potential inconsistencies with reclamation guidelines for the oil and gas industry that have persisted in the green (forested) zone of Alberta. The research was designed to identify factors that contribute to poor ecological recovery on upland boreal oil sands exploration sites and assess whether they could be mitigated during construction and/or reclamation. The boreal forest is a mosaic of patches expressing variability in species richness and composition as a direct reflection of site hydrologic regime, nutrient and light availability and disturbance history (Bergeron et al 2014, Beckingham and Archibald 1996, Bonan and Shugart 1989). A major component of site recovery is regeneration of plant communities from surviving vegetation, seed banks and buried propagules; these components can vary with site disturbance history, including type, frequency and intensity. Thus, predicting reclamation outcomes within this mosaic can be difficult.

While much attention has been directed towards cumulative effects of energy extraction in the vast, mineable (surficial) portion of the Athabasca Oil Sands, some assert that cumulative effects of in-situ bitumen development are far greater and expected to increase rapidly (Nishi et al 2013). Increasing public awareness of cumulative effects and industry contributions to biodiversity reduction and habitat fragmentation are driving stakeholders to reduce the overall footprint of energy extraction (Powter et al 2011). Among others, the Pembina Institute and Canadian Parks and Wilderness Society have been instrumental in raising awareness of environmental impacts from the oil industry. Schneider and Dyer (2006) estimated that in-situ operations in the Alberta boreal zone will affect 138,000 km^2, leading to almost 12,000 km^2 of cleared forest and 441,600 km of roads. They asserted that current reclamation practices are insufficient for boreal forest recovery, and industry is continuing development at an ecologically unsustainable level. Ongoing habitat reduction and fragmentation, hydrologic discontinuity, reduced forest regeneration and productivity, and increased human access due to industrial disturbance and associated patterns of land use are likely to exacerbate the ongoing decline in forest quality, leading to extirpation of endemic populations and impaired ecological function over the long term (Nishi et al 2013).

Alberta white zone (agricultural) and forestry guidelines have strongly influenced the establishment of indicators for reclamation success in the boreal forest. However, these are not always appropriate analogs for the variety of disturbances that are generated by the construction of oil and gas infrastructure and associated well sites. During initial study implementation, combinations of construction and reclamation techniques on well sites were used to determine if the degree of disturbance and damage to existing vegetation and/or legacy propagules could be reduced. A five year evaluation showed significant differences among treatments. Several sites reclaimed between 2004 and 2006 using different treatment combinations were examined, and used to make recommendations for industry improving well site reclamation in the boreal zone (Osko and Glasgow 2010). Given that ten years has now passed since these treatments were undertaken, we have re-evaluated reclamation success beyond the initial establishment phase of succession, and assessed longer term implications of the various techniques used.

2. THE BOREAL FOREST ECOSYSTEM

The boreal forest is a circumpolar ecosystem covering 11 % of the earth's surface (Bonan and Shugart 1989) with broad economic and ecological importance. Throughout North America, Europe, Russia and Scandinavia, the boreal is an important source of timber and fresh water, plays a key role in global climate regulation and hydrologic cycling (Hassan et al 2005), is critical habitat for many aquatic and terrestrial species (Venier et al 2014, Kreutzweiser et al 2013), and has cultural value for many peoples (Hassan et al 2005). Canada has 28 % of the global boreal forest, second only to Russia (60 %) (Brandt et al 2013).

The Alberta boreal forest covers more than half the province, of which 25 % is boreal mixedwood (Figure 1.1) (Natural Regions Committee 2006). The region is characterized by gently rolling to hummocky moraine receding to lacustrine flats underlain by Cretaceous shales (Natural Regions Committee 2006, Rowe 1972). Surficial materials range from fine eolian and glaciolacustrine deposits, to coarse glaciofluvial deposits (Rowe 1972). Unlike eastern Canadian boreal forest, where the humid to perhumid climate promotes development of Podzolic soils (Soil Classification Working Group 1998), soil development in Alberta boreal forest typically proceeds from Dystric (some Eutric) Brunisols in dry sandy areas to Gray Luvisols in mesic and imperfectly drained areas with Solonetzic intergrades (Natural Regions Committee 2006). Lowlands feature Organic and Gleysolic soils in wet to poorly drained areas. The region is characterized by short cool summers and long cold winters (Brandt et al 2013) with most precipitation in summer months (~480 mm yr^{-1}) (Natural Regions Committee 2006).

Boreal forest is generally comprised of cold tolerant species (Brandt et al 2013) in the northern hemisphere between 50˚ and 65˚ N latitude (Molles 2002). Dominant plant species are *Populus tremuloides* Michx (trembling aspen), *Populus balsamifera* L (balsam poplar) and *Picea glauca* (Moench) Voss (white spruce) upland forests. *Pinus banksiana* Lamb (jack pine) and *Cladina* species (Nyl) Nyl (reindeer lichen) dominate dry, coarse soils. Lowlands are dominated by *Picea mariana* (Mill) Britton, Sterns & Poggenb (black spruce), *Larix laricina* (Du Roi) K Koch (tamarack) and *Sphagnum* L (sphagnum) mosses (Natural Regions Committee 2006).

Dominant upland forest types include trembling aspen in recently disturbed areas, mixedwoods that may contain *Betula* species (birch) including *Betula papyrifer*a Marshall (paper birch) and Betula neoalaskana Sarg (Alaska birch) and balsam poplar, and increasing to dominating amounts of white spruce and *Abies balsamea* (L) Mill (balsam fir) in older stands (Natural Regions Committee 2006, Rowe 1972). The Natural Regions Committee (2006) described the reference ecosite of the Central Mixedwood Natural Region as aspen, or aspen and white spruce mixtures in a range of proportions on Gray Luvisols of variable texture. Beckingham and Archibald (1996) found these ecosites could be further categorized into ecotypes primarily by either *Viburnum edule* (Michx) Raf (low bush cranberry), *Rosa acicularis* Lindl (prickly wild rose), *Alnus viridis* (Chaix) DC (green alder) or *Cornus sericea* L (red osier dogwood) as the leading tall shrubs in the understory, and commonly associated with *Cornus canadensis* L (bunchberry), *Aralia nudicaulis* L (wild sarsaparilla), *Rubus pubescens* Raf (dewberry) and *Calamagrostis canadensis* (Michx) P Beauv (blue joint). The understory is further comprised of forbs and shrubs from many families including Asteraceae, Violaceae, Ericaceae, Orchidaceae, Caprifoliaceae and Saxifragaceae. This understory is dense and productive in young and open forests, and reduces with decreasing light levels and canopy closure, particularly when coincident with increasing conifer dominance. Feather mosses are common as this forest matures and becomes increasingly dominated by white spruce.

Trembling aspen is primarily a clonal species and vigorously resprouts following disturbance. Individual trees can live up to 150 years, but colonies in our region are estimated to be 8,000 years old, having established after the last glacial retreat (USDA 2003). This species also reproduces by seed on mineral substrates, but requires continuous moisture for seedlings to establish (USDA 2003). Due to its vigorous suckering, aspen stands can be self replacing in absence of a viable seed source of white spruce.

White spruce can live up to 250 years in Alberta (Day 1972) and begin seed production as early as four years (Sutton 1969). It is capable of vegetative reproduction through layering, although this is more common further north (Nienstaedt and Zasada 1990). Its foremost reproductive strategy is wind dispersed seed, with massive seed production in mast years. White spruce seeds can germinate in newly disturbed areas on exposed mineral soil, humus and woody substrates (Peters et al 2006, Purdy et al 2002, Zasada and Gregory 1969, Eis 1967). Under developed canopies, seedlings will establish on woody debris in various stages of decay (Gärtner et al 2011, Beach and Halpern 2001, Christy and Mack 1984, Day 1972), and feathermosses (LaRoi and Stringer 1976).

The boreal mixedwood is a broad and diverse transition zone from the deciduous Aspen Parkland to the south, to the sclerophyllous forests of the north. It is a mosaic of vegetation patches expressing considerable variability in species richness and evenness as a direct reflection of site hydrologic regime, nutrient and light availability, together with disturbance history. The ecology of the region is strongly influenced by fire (Brandt et al 2013, Hart and Chen 2006, Kneeshaw et al 2011, Weber and Stocks 1998, De Grandpré et al 1993).

3. DISTURBANCE AND SUCCESSION

3.1. Natural Disturbance And Succession

Diversity in the North American boreal forest is resultant of 12,000 years of vegetation development in conjunction with disturbance (Brandt et al 2013, Weber and Stocks 1998). Variation in proportional representation of plant species across the landscape is a function of abiotic site conditions and disturbance history. Disturbance history, frequency and intensity, combined with landscape position, hydrology, soil texture and nutrient, light and water availability mainly determine propagule distribution and establishment (Bergeron et al 2014, Bonan and Shugart 1989).

The boreal forest is prone to biological, climactic and pyrogenic disturbances, which affect the forest uniquely. Disturbance types play different roles in successional development at stand and/or landscape scales. Although natural primary succession may occur in Alberta, such as after mining or landslides, it is uncommon. As disturbance selectively eliminates species from the community and changes physical structure and composition of the landscape, secondary succession is initiated, with results depending on disturbance frequency and intensity, and the size or spatial scale at which it occurs. Disturbance therefore resets boreal communities to an earlier stage of forest ecological development, with a gradient of early successional possibilities, as determined by the disturbance size, frequency and intensity (De Grandpré et al 1993).

Biological disturbances affect forests by selectively removing one or more plant species from the community over a prolonged period through insect outbreaks, disease and herbivory. *Malacosoma disstria* Hubner (forest tent caterpillar) has had severe impacts on trembling aspen in the western boreal, especially in conjunction with drought (Cooke and Roland 2007). Disturbance due to herbivory by mammals is common throughout the boreal forest. Ungulates including *Odocoileus virginianus* Zimmermann (white tailed deer), *Cervus canadensis* L (elk), and *Alces alces* Clinton (moose) browsing of deciduous trees can perpetuate self replacement of root suckering species such as trembling aspen and balsam poplar, or initiate release of coniferous understory species such as white spruce and balsam fir (Franklin and Harper 2016, Pastor and Naiman 1992). Moose and deer will also browse balsam fir saplings, potentially reducing their presence in late successional forests (Jean et al 2015, Potvin et al 2003, Brandner et al 1990). *Castor canadensis* Kuhl (beaver) engineer forest structure and succession through removal of trembling aspen and dam building (Rosell et al 2005). White spruce seedlings are prone to herbivory by *Lepus americanus* Erxleben (snowshoe hare) limiting their growth and survival (Bergeron et al 2014), and thus locally slowing or preventing mixedwood forest development.

Weather and climatic disturbances tend to occur at the stand scale, including windthrow, frost, and ice damage. Most often these disturbances create canopy gaps, but can affect larger areas via flooding and drought. All disturbance types are recognized as important in promoting species diversity and maintenance of ecological processes, although the latter is performed within the overarching disturbance regime of fire.

Boreal forest disturbance history is heavily influenced by fire with a return period of 50 to 200 years, and up to 500 years in wet regions (Bonan and Shugart 1989). Fire directly affects the pool of plant species available for regrowth (Zackrisson 1977), and in the process shapes boreal forest species characteristics, maintains diversity and controls successional development (Kneeshaw et al 2011, Hart and Chen 2006, De Grandpré et al 1993). Plant species within this forest have developed various adaptations to fire, and some species such as jack pine depend on fire for regeneration (Kneeshaw et al 2011). Weber and Stocks (1998) asserted that the fire adapted characteristics of major boreal tree species have been in place since the last glaciation, 15,000 years BP. Examples of these adaptations are presented in Table 1.1; although an extensive list could be produced of the number of boreal plant species that have developed adaptive responses to fire, including vegetative reproductive strategies and seed bank longevity (Kenkel et al 1997). These characteristics can be grouped into three categories based on life history strategies described by Grime (1979); ruderal, competitive, or stress tolerant species. These characteristics in combination with the relative abundance of propagules present, post-disturbance site conditions, and post-disturbance climate and weather determine which species establish, and those that may be eliminated or emerge through successional development.

Succession in the boreal can be viewed through many hypothetical lenses, as there are a variety of pathways through which mature climax forest is reached. The classical linear definition is that succession is a unidirectional process of community replacement towards a stable, self replacing climax, although this is difficult to apply in boreal ecosystems (Johnson and Miyanishi 2007). Jack pine, aspen, birch and black spruce stands are essentially self replacing (auto successional) post-fire, and thus often lack discernable sub-climax seral stages that suit this definition (Weber and Stocks 1998). Prolonged self replacement is often the result of frequent repeated disturbance (Bergeron et al 2014), and although it does not lead to seral plant group replacements, it does lead to cohort based structural seral stages. These are subtly distinguished process based stages whereby the initial establishment community goes through self thinning, followed by stand re-initiation, and towards an old growth community maintaining the same dominant species. As with all forests, each stage differs in ecosystem processes such as carbon storage and sequestration, nutrient and hydrologic cycling and habitat provision within the landscape.

Genesis and development of the classical definition and understanding of succession recognized disturbance only as an event initiating succession. Succession is often assumed to proceed without further disturbance; this neglects the critical link between disturbance history and the ongoing role of ecological processes (Johnson and Miyanishi 2007). Burton et al (2003) described what was commonly observed as the boreal mixedwood successional pathway in Alberta; colonization by pioneering trembling aspen followed by white spruce invasion and a prolonged co-existence of these species in varying proportions with potential (in absence of disturbance) to reach the climax stage of white spruce. Certain tree species are well adapted to respond to canopy removal (eg trembling aspen) and others require shade (eg balsam fir). In a very generalized succession model for the boreal forest, the plant species present proceed from shade intolerant to shade tolerant over time, although there are a variety of possibilities.

From research conducted in the North American boreal region, Bergeron et al (2014) asserted that the array of successional pathways possible for boreal mixedwoods can be explained by multiple stochastic factors that range across spatial and temporal extents, and are further punctuated and perpetuated by disturbance. In the Boreal Plains of Alberta, the historic fire cycle of 68 years has changed to 239 years with moderation of continental climate and fire suppression (Kneeshaw et al 2011). However, the historic pattern has created the site specific legacy from which succession proceeds. The species available and able to re-establish immediately post-disturbance will affect what follows and how the regenerating area will respond to further disturbance (Bergeron et al 2014). Initial post-disturbance propagule availability is therefore a key predictor in stand development, which is determined by fire history and plant reproductive strategies (Kneeshaw et al 2011, Nguyen-Xuan et al 2000).

Sites with frequent fire regimes will have increasingly more ruderal and potentially invasive species establishing over time, as they are well adapted to repeated disturbance and thrive in a broad range of environmental conditions. In this scenario, the proportion of ruderal and stress tolerant propagules on such sites is likely to increase, which can in turn significantly impact forest development (Lieffers et al 1993). Alternately, a site with a long fire return interval will have had less seed and propagule production from opportunistic species, leading to a legacy pool containing more shade tolerant species, and plant species that are not well adapted to repeated disturbance. Proportions of these species vary throughout the forest; no fire is ever evenly distributed across the landscape, leaving patches of less burned or even untouched forest area. This uneven distribution occurs due to wind direction and turbulence, geographic and aquatic barriers, fuel loads generated by certain forest types and ages of stands. Unburned patches can become nucleation sites for regrowth, leaving mother plants on the landscape to contribute wind and animal dispersed seed to the seed bank and propagule pool. Thus, a similar disturbance within two different mixedwood areas can lead to different seral stages within the same successional timeline.

The net result of 12,000 years of vegetation development, coincident with various disturbances, is that northern Alberta hosts a forest that expresses its diversity in distinct patches (Bergeron et al 2014, Weber and Stocks 1998). The plant species that are present are a function of the abiotic elements on site, including light, nutrients and soil water availability, which in turn vary with landscape position, soil texture and hydrology, in combination with what plant species have or have not been filtered out of the local system by disturbance frequency and intensity (Bonan and Shugart 1989).

3.2. Human Disturbance

Human disturbance in northern Alberta has only been widespread in the past century. Although much of the southern portion of the boreal mixedwood forest has been extensively cleared for agriculture, this practice is limited to the north due to difficulties associated with poor soil quality, short growing season and limited presence of private land. Approximately 1.6 million ha of the Boreal Forest Natural Region is allocated under grazing leases for beef cattle (Alberta Agriculture and Forestry 2015). Hunting, trapping and fishing have been practiced by indigenous people for generations in boreal regions, but these activities have increased with population growth and increased forest access.

There have been several decades of timber harvest in the boreal forest, and sizeable tracts of northeastern Alberta have been extensively managed for timber production since the 1980s (RAMP 2014). Prior to the 1990s, post-harvest operations focussed on monocultural re-establishment of white spruce to meet projected future market demand for timber. Growing awareness of biodiversity and social values associated with the boreal forest, and an increased market demand for aspen has shifted forestry practices toward mixedwood management, which by the mid 1990s became the utmost research priority in the management of Alberta forests (Grover and Fast 2007, MacDonald 1995, Forest Research Advisory Council of Canada 1994, Boyle 1992, Suffling et al 1988). Thus managing for development of mixed trembling aspen and white spruce stands is of key interest in Alberta.

Oil extraction has been active in the boreal region of north eastern Alberta since 1913. As refining processes improved, extraction significantly accelerated during the 1950s. Since then the area impacted by surface mining of oil sands has steadily increased north of Fort McMurray. The Athabasca Oil Sands underlay 140,000 km^2 of Alberta's boreal forest, of which approximately 20 % is accessible by open pit mining (Alberta Geological Survey 2013) (Figure 1.2). The remaining 80 %, which accounts for 97.5 % of the surface area of the deposit, is deep beneath the earths' surface and only extractable using in-situ technologies (CAPP 2014). In-situ technologies have been in development since 1910, although they only became commercially feasible in the late 1980s with Imperial Oil's cyclic steam injection plant in Cold Lake (Wikipedia 2014). A similar technology, steam assisted gravity drainage (SAGD), is currently used in the Athabasca Oil Sands Region (Government of Alberta 2013). The process requires a central processing facility to produce steam to liquefy heavy oil in place; the liquefied oil is then pumped to the surface. Multiple arms of twinned pipeline stretch from the central processing facility to extraction sites within its radius to simultaneously inject steam underground in heavy oil deposits, and extract liquefied bitumen. With dozens of Alberta and global producers using the technologies, in-situ production methods account for over half of Alberta's oil production (Government of Alberta 2013).

4. OIL SANDS EXPLORATION DISTURBANCE AND RECLAMATION

Before the necessary infrastructure for extraction and processing can be put in place, in-situ oil sand processors must delineate the most geologically appropriate site for extraction to maximize recovery. This process is required by the National Resources Conservation Board and companies must drill a minimum of eight oil sands exploration wells per section, per lease (Osko and Glasgow 2010); this number often increases as more information is gathered to delineate the deposit. In the study area being assessed in the current investigation, 16 or more wells were required per square mile (260 ha).

When an exploratory drill site is chosen, access roads must be cleared, vegetation removed and a stable platform put in place for the drilling rig. This often requires soil removal and storage, which is later replaced as part of the reclamation process. Historically, the boreal forest has not been exposed to this type (mechanical clearing) and intensity of disturbance. Mechanical disturbance of soil and associated deforestation is more comparable to landslide or slumping events, which rarely occur in the boreal. There is an abundance of information regarding boreal forest recovery after a burn (Peters et al 2006, Greene et al 1999, Weber and Stocks 1998, Zackrisson 1977) and the silvicultural practices needed to achieve forest regeneration after timber harvest (Government of Alberta 2016, Burton et al 2003), although little is known about the long term effects of oil sands exploration via surface well disturbances.

Relative to open pit mining where the majority of the disturbance occurs across large localized areas in a very intensive and generally uniform manner, ultimately leaving an anthropogenic landscape, oil sands exploration well sites and steam assisted gravity drainage operations are less intrusive. Instead, they leave their footprint in a variety of patterns through the boreal forest in the form of seismic lines, pipelines (above and below ground), power lines, access roads, centralized upgrading facilities and well pads. Open pit mining operations require vast reclamation projects, but have ample space to bring in large machinery and materials. In contrast, oil sands exploration well operations are smaller disturbances, although they are more numerous and scattered across a much greater area to which access is limited both spatially and temporally. For this reason, reclamation targets must be clear and techniques efficient during the construction and reclamation phases of development. As forest regeneration and access road closure by planting, seeding and regrowth are often the desired outcomes, re-entering sites to amend a reclamation project that has not been successful generates further disturbance and is financially undesirable.

4.1. Oil Sands Exploration Well Construction

In Alberta, well construction occurs under frozen conditions during winter months, which allows for access to sites that would be otherwise inaccessible and reduces the need for more permanent road construction (Osko and Glasgow 2010). Once a site is selected for oil sands exploration, vegetation must be cleared and a level working surface prepared for assembly of the drilling rig. Merchantable timber is salvaged for processing by the company who retains the forestry rights to the lease. The remaining woody materials such as logs, small tree boles, branches, stumps, roots and understory debris remain on the site.

Space must be available to accommodate the rig and drilling equipment, vehicles and mobile offices with appropriate safety spacing. Most oil sands exploration sites require an area 70 m x 70 m in size. In contrast, conventional oil and gas wells require 100 m x 100 m (Osko and Glasgow 2010). Site managers often choose to further modify woody materials if there is an excess amount, which can include mulching and/or burning, with materials initially piled to one side or corner of the lease to make room for construction operations.

Vegetation removal resembles fire disturbance by greatly reducing the carbon stored on site, and carbon availability for future successional stages. What remains in variable amounts is slash and debris that can be added to the slow to moderately slow decomposition pool. It is up to the site manager to choose how it is redistributed, but its volume and size affects several other processes; it can increase soil water retention and reduce soil temperature, thus slowing decomposition rates and nutrient cycling. While woody debris can create variability of microsites for regeneration (Vinge and Pyper 2012), it may also inhibit regrowth (Landhäusser et al 2001). Vegetation removal further resembles fire disturbance in that the canopy is removed, favouring regeneration of shade intolerant species.

A flat surface is required for assembly of the rig. If the site is relatively uniform in slope, this can be achieved by using low disturbance methods. Excess slash or mulch, together with snow, can be used to fill small depressions, and a stump grinder used to level stumps. Lower areas may be raised using water to build up ice, and hence are often referred to as iced in. For most of the low disturbance sites in this study, construction occurred overtop a stable platform of snow, ice and mulch (Osko and Glasgow 2010). This is a preferred site preparation method as low disturbance construction has been shown to be beneficial for regeneration of aspen stands (Bachmann et al 2015) and can be completed at a reduced cost relative to conventional methods, although it may induce compaction of soils on some sites.

Conventional methods of levelling occurs on sites that are topographically variable, but may also be used depending upon the size of the rig, depth of drilling or expected life span of production for conventional wells. Surface soils are stripped and a level foundation for the drilling rig is created upon the sub-surface soil. Soil stripping usually requires two passes; first the topsoil consisting of the LFH and A horizon is removed, followed by removal of the underlying B horizon (Osko 2016).

Soil depth is variable in the boreal; if the A horizon is less than 15 cm, Alberta guidelines require a minimum of 15 cm, including a portion of the B horizon, to be conserved (ESRD 2013). This would include the LFH and A horizon and part of the B horizon, with the exception of where the B horizon has physical or chemical limitations that make it unsuitable for use in reclamation. For example, bedrock, rock and gravel or a sub-surface horizon indicating Solonetzic soil (Bnt) (ESRD 2013) could impede revegetation by impeding drainage, rooting or germination if used as a reclamation material. In practice, equipment operators often use soil colour change as an indicator for stripping, thereby stripping first the LFH (depending on thickness), then the A and then the B horizons (Osko 2016).

Conserved soils are stored at the lease edge and then replaced within a few weeks, mostly within the same winter, and occasionally the following winter during reclamation (Osko 2016, Osko and Glasgow 2010). In this study, soils were stored in one progressive pile, or two separate piles. Space availability may require that one pile be made, but this can inevitably lead to mixing of soil horizons and potential of further altering the physical and chemical properties of excavated soils. Using separate piles to reduce the amount of mixing that occurs throughout the disturbance may be beneficial. However, the extent of impact upon the seed bank, propagules, soil bacteria and microfauna and nutrient cycling as a result of short term winter storage have not been quantified.

4.2. Oil Sands Exploration Site Reclamation

Once a well is abandoned, the casing is cut, sealed and capped at a depth of 1 m below the soil surface, and buried (Osko and Glasgow 2010). At sites constructed with low disturbance methods, the ice is ripped and woody material evenly spread across the site. On conventionally constructed sites, soils are replaced in the reverse order that they were removed such that the LFH and A horizon are placed on top, and contoured as needed to suit the local topography. Remaining woody debris is distributed across the site. Study areas under investigation here have been left to revegetate naturally as the previous requirement for seeding grasses was removed in 2002 (Osko and Glasgow 2010). More recently, intensive tree planting programs have been undertaken whereby planting crews and nursery grown seedlings (pre-selected tree species based on local ecosite prescriptions) are flown in by helicopter during summer months. Planting has the potential benefit of fast tracking the establishment of trees, in turn leading to more rapid revegetation and restoration of natural ecosystem functions.

5. ASSESSING RECLAMATION SUCCESS

Historically, industrial and oil and gas development began in the southern region of Alberta and reclamation guidelines were developed with the intent of restoring agricultural end land uses. Well site reclamation guidelines focused on returning land to equivalent capability (Government of Alberta 2014), measured as the ability of a site to support vegetation (Osko and Glasgow 2010) with the goal of preventing erosion and soil degradation. This practice achieved the goal of conserving soils, but could limit a site's potential to fulfill other important ecosystem functions, including revegetation to the historical plant community. Osko and Glasgow (2010) observed that this philosophy influenced reclamation practices as industry progressively advanced northward into the boreal forest. The impact of this is visible on disturbed sites that were abandoned as early as the 1960s, exhibiting little to no forest re-establishment.

In 1993, the province initiated a movement to redirect the focus of reclamation toward ecological function and reducing cumulative effects with the Environmental Protection and Enhancement Act (Powter et al 2011). Although progressive legislation in itself was an improvement, recent updates to the guidelines show there is still a significant policy gap between the requirements for reclamation of forested versus cultivated and native grasslands (Table 1.2).

Alberta forestry guidelines have also had a strong influence on generating indicators for reclamation success in the boreal region, because the end land use is often to produce merchantable timber (Straker and Donald 2011, Oil Sands Vegetation Reclamation Committee 1998). However, post-harvest conditions are not always a suitable comparative analogue for the range of disturbances that the oil and gas industry creates.

The 2000 well site reclamation criteria were updated in 2010, and again in 2013 (ESRD 2013). They now recognize the value of woody debris in forested landscapes (Table 1.2) and include guidelines for soil replacement (texture and depth), which had been previously ignored. However, there are still no target criteria for success, for example in plant height and density, because best management practices that will provide consistent, predictable and satisfactory reforestation outcomes have yet to be developed. Despite a decisive External Directive by Environment and Sustainable Resource Development (ESRD 2009), which recognizes the potential negative impacts of mulch on forest regeneration, the 2013 update to the 2010 well site criteria remains tolerant of mulch use, stating that an excess of mulch can be detrimental and may require management, but does not restrict its use in depths of 5 cm or less (ESRD 2013). This policy neglects to consider site specific conditions that may prove mulch to be beneficial or limiting to the achievement of the target forest type.

Definitive guidelines for use of mulch and other knowledge gaps can only be addressed by continued study of the long term impacts of in-situ disturbance in the boreal forest. Appropriate assessment of the ramifications of different construction and reclamation techniques are necessary so that predictive models for reclamation success can be developed. These models can then serve as a template for industry when making management decisions to achieve an early successional community for the target forest type within the boreal mosaic (ESRD 2013).

Long term data collection and analysis are required to bring about meaningful change in industrial practices. This is evident in studies regarding the influence of coarse woody debris on natural revegetation (eg Mackenzie 2013, Naeth et al 2012, Vinge and Pyper 2012). Large woody materials left after site clearing were historically burned or mulched, but more companies are now conserving them and spreading coarse woody debris across the site to improve reclamation outcomes. This is now a recognized method in the Alberta reclamation criteria. However, clarification of the long term implications of woody material management, soil and propagule management, and low disturbance well site development methods is needed.

6. ECOLOGICAL IMPACTS OF DISTURBANCE AND RECLAMATION PRACTICES

6.1. Soil Disturbance On Planted Spruce And Regenerating Vegetation

Soil management in construction, storage and reclamation phases of disturbed sites has a direct impact on propagule survival, and therefore vegetation recovery. Soil disturbance for in-situ operations ranges from low disturbance iced in construction, to soil removal and replacement. Protection of the forest floor is a key benefit of iced in construction for aspen regeneration (Bachmann et al 2015). With low disturbance methods, soil layers remain intact but compaction varies with the degree and depth of frozen conditions. Freezing is reduced during winters with above seasonal temperatures (Osko and Glasgow 2010).

Where sites have been excavated, compaction can occur in sub-surface soils from heavy equipment, including the rig itself, and during soil replacement. Compaction can affect soil texture, hydrologic flow and nutrient cycling and availability (Startsev and McNabb 2007, Corns and Maynard 1998, Wang and Klinka 1996). Bulk density can increase when compaction reduces soil porosity, leading to nutrients being more tightly bound within soil aggregates (Corns 1987). Compaction reduces available space for water movement and gas exchange and restricts root growth, which is particularly significant when bulk density approaches 1.5 Mg m^{-3} (Corns 1987). Low-disturbance construction maintains the integrity of the seed bank and sub-surface propagules within the soil matrix, except where compaction occurs to the degree that it destroys them or inhibits their germination and/or survival.

Effects of compaction can persist in Alberta boreal forest soils for decades due to expansion resistance of the regionally abundant mica clays (Corns 1987). Once compacted, reduced soil aeration significantly impacts many soil parameters that affect forest productivity (Startsev and McNabb 2007, Wang and Klinka 1996) and is a limiting factor in white spruce growth (Kabzems 2012, Nienstaedt and Zasada 1990). Spruce seedling growth has been significantly reduced with increasing soil bulk density (Duan et al 2015, Corns 1987). Compaction can impact structural development and productivity within aspen dominated forests (Curzon et al 2014, Kabzems 2012, Stone and Eliof 1998). Impacts to aspen regeneration density incurred as a result of compaction can be reduced by restricting site disturbance to winter months (Renkema et al 2009, Stone and Eliof 1998) and when soils are relatively dry (Corns and Maynard 1998).

Compaction can be alleviated by a number of methods. Management can prevent or reduce compaction by not operating on sites while the soil is wet, using equipment that has reduced ground pressure, reducing the number of passes for soil replacement (Alberta Transportation 2013), and using woody materials to cover and protect driveable areas (ESRD 2009). During reclamation, there are many tools available for decompaction of soils. For example, the site can be ripped prior to soil replacement, and disced with subsequent replacement of layers to alleviate compaction induced by multiple passes of machinery during replacement (Alberta Transportation 2013). If soil was not stripped, harrowing may alleviate compaction (Alberta Transportation 2013). These mechanical treatments can increase soil porosity, infiltration and water retention, where compaction may have otherwise impeded revegetation.

On sites where excavation is required to achieve landscape levelling, there is unavoidable disarrangement of the soil (mixing of layers including LFH, A and often B horizons) and propagules, with significant interruption of natural biogeochemical and pedogenic processes.

During the excavation and storage processes, there is a temporary reduction in bulk density that contributes to the loss of fine particulate matter, and subsequent change of soil texture.

With aggregate loosening, there is an increase in the surface area of soils exposed to the atmosphere, and if temperatures become unseasonably high (greater than 7 ^{o}C), nitrogen volatilization and nutrient leaching may occur (Brady and Weil 2010). Through the winter months, excavated soils no longer thermally protected by snow and organic material are more commonly exposed to lower temperatures, thereby losing microbial and microfaunal populations to desiccation, which would impact potential post reclamation productivity.

Some soil disturbance is considered beneficial for tree establishment. Soil mixing by mechanical site preparation is a preferred treatment for promotion of white spruce seedlings in western Canada's boreal region (Archibold et al 2000, Boateng et al 2006) where soil mixing and mounding treatments improved spruce survival and growth (Gradowski et al 2008). This is likely due to the abundance of moss on the forest floor in coniferous systems, which keeps soil cool, and has been identified as a significant growth limiting factor (Landhäusser et al 2001). Litter quality in deciduous forests is higher and readily decomposable (Gradowski et al 2008).

Overall improvement in nutrient availability is therefore possible by soil mixing, although the effect is temporary (Lupi et al 2013). Propagules are destroyed through breakage or desiccation, which can impact regeneration of many species including trembling aspen. In some cases, presence of viable propagules may increase. For example, blue joint has an extensive rhizomatous root system that may fragment with disturbance and lead to vigorous re-sprouting (Lieffers et al 1993). The grass can quickly take over newly disturbed sites, and significantly impact survival and growth of juvenile spruce and aspen through multiple competitive means (change in light, nutrients, water and temperature) above and below the soil surface. Thus, disturbing soil not only changes its composition and structure, but also changes the proportion of plant species available in the propagule pool, and therefore alters successional development.

6.2. Soil Storage Methods On Planted Spruce And Regenerating Vegetation

Oil sands exploration sites have a typical life span of a few winter months. In this study, soils were stored in one progressive pile, or two separate piles. Excavated soils are temporarily piled at the edge of the site to make room for well site operations. There have been a few studies in various ecosystems on effects of stockpiling salvaged soils, and fewer still in Alberta boreal soils. Mackenzie (2013) found that significant reductions in propagule viability could occur within eight months of storage, although the impact was less in winter than fall excavated soils. Impacts on propagules in stockpiles from winter excavated soils were further reduced if soils did not thaw. Some losses would occur due to exposure to freezing temperatures. Desiccation due to low atmospheric water vapour content would occur in roots and seeds with low resistance to water loss. Soil bacteria and microfauna were similarly impacted by exposure (Visser et al 1984), reducing soil productivity and therefore nutrient availability for regenerating plants.

With storage for a short time in low temperatures, it is unlikely that complex chemical changes would occur as observed in soils stockpiled for longer periods, over summer months, or in temperate climates (Mackenzie 2013, Ghose 2001, Visser et al 1984). Mackenzie (2013) found that when temperatures fell below freezing, soil porosity and oxygen content increased. This could increase the impact of desiccation on soil propagules and bacteria. Chemical changes may occur due to prolonged unseasonal warming events, or if soils were excavated to too great a depth including calcareous or saline deposits in the salvage piles. These could alter pH or electrical conductivity during storage and soil replacement. Both Mackenzie (2013) and Ghose (2001) found that stockpiling soils increased bulk density. The increase was dependent upon soil textural properties and height of the pile. The progressively piled soils would necessarily be taller than the separately piled soils in this study, and may increase propagule breakage.

6.3. Woody Debris On Planted Spruce And Regenerating Vegetation

Woody debris consists of all non-merchantable woody materials remaining on site following forest disturbance. This includes the remains of trees in the form of logs, small tree boles, branches, stumps, roots and understory debris which were for many years removed from sites in Alberta for the prevention of wildfire, but have been increasingly retained in recognition of their ecological value (Vinge and Pyper 2012).

Wood mulch is a type of woody debris and is approved by the Alberta Government to minimize soil disturbance induced by industrial activities when used to create a driveable wood fibre surface (ESRD 2009). It is often used as a reinforcing component in creation of a stable working surface in some iced in well site construction techniques (Osko and Glasgow 2010). However, wood chips can have negative impacts on biotic communities. Corns and Maynard (1998) found that mulch at depths greater that 10 cm reduced aspen plant community densities and cover, with no difference in aspen density when mulch was 5 cm or less. More recent research has shown mulch spread at depths greater than 4 cm impedes aspen regrowth by imposing a physical barrier and slows regeneration by insulating the soil and maintaining cool temperatures further into the growing season (Vinge and Pyper 2012, Landhäusser et al 2007). Phenolic compounds in mulch leachate have the potential to inhibit regrowth of many species in aspen environments (Conlin 2001). The smaller, fine nature of mulch does not provide the same range of ecosystem benefits as larger coarse woody materials.

Coarse woody material beneficially contributes to well site reclamation, fulfilling short and long term objectives. Coarse woody debris positively influences plant diversity (Brown and Naeth 2014, Harmon et al 1986), survival of seedlings and structural diversity (Brown and Naeth 2014, Christy and Mack 1984). Brown and Naeth (2014) found that in Alberta's boreal, spreading coarse woody debris in reclamation reduced bare ground and inhibited the entry of non-native species. They further noted that use of coarse woody materials reduces soil temperature and soil water range extremes; findings similar to those discussed by Amaranthus et al (1989).

Coarse woody materials can assist in fulfilling long term end land use objectives in forest ecosystems. Post-disturbance, white spruce will readily establish within three to five years on mineral soil or humus, when ample seed is available, such as when disturbance coincides with a mast year (Peters et al 2006, Purdy et al 2002, Zasada and Gregory 1969, Eis 1967). In absence of exposed mineral or humus surfaces, conifers preferentially select sound and decayed woody debris as a germination substrate in both recently disturbed forests (Beach and Halpern 2001), and underneath established deciduous overstory for ongoing recruitment (Gärtner et al 2011, Christy and Mack 1984). Decayed woody materials can be important recruitment substrates for white spruce in mid to late successional forests in Alberta (Gärtner et al 2011, Lieffers et al 1996, Peters et al 1996).

Rotting logs may provide a favourable rooting substrate with ample moisture and increased access to light, being somewhat elevated above litter fall and spatially removed from ground layer competition (Lieffers et al 1996, Christy and Mack 1984, Waldron 1966, Koroleff 1954). Spreading coarse woody materials as part of a forest well site reclamation strategy may beneficially contribute to reclamation goals and mixedwood forest succession over the long term, and positively contribute to end land use objectives by assisting the development of diverse forests and mixedwood stands for future harvest.

6.4. Planted Trees On Regenerating Vegetation

Disturbed boreal well sites in this investigation have been both planted with trees and left to revegetate naturally. Many sites still lack canopy development due to competition with regenerating native grasses and shrubs. It is uncertain how long a site will remain dominated by grasses and shrubs, or if native forest will re-develop.

It is well recognized that implementing measures to assist reforestation may not only promote a sites ability to return to a forested ecosite, but promote diversity and ecosystem function over the long term (Kuuluvainen 2002). Trees are the ecosystem engineers of the forest, providing structural diversity and controlling microclimate conditions that in turn, influence all other plant species in their vicinity. With a greater amount of regeneration niches available, more species may re-establish more quickly whose interactions contribute to the overall productivity of the forest both above and below ground.

7. RESEARCH OBJECTIVES

The objective of this research is to identify factors that contribute to successful revegetation of well sites in Alberta boreal forest so best management practices for construction and reclamation can be developed. For this study, success is defined as factors that facilitate successional development on a path likely to converge with the surrounding forest, and that promote survival and growth of planted trees. Factors include construction and reclamation methods and site conditions.

Specific research objectives are to assess the effects of the following on plant community development.

- Low soil disturbance (iced in) and conventional soil stripping during construction.
- Woody material management (mulched versus spread or windrowed slash).
- Single (progressive) and separated (LFH, topsoil, subsoil) pile storage.
- Site conditions such as soil type and surrounding vegetation community.
- Soil properties.
- Time since disturbance on well sites constructed and reclaimed with different methods.

8. THESIS FORMAT

This overview of Alberta's boreal forest and the challenges facing successional development and forest management provide the background for the thesis research and summary chapters. Chapter 2 addresses successional development of boreal forest plant communities on reclaimed well sites. Chapter 3 explores effects of well site disturbance on planted spruce and naturally regenerating trees focusing on aspen to determine factors or combinations of factors that contribute to poor ecological recovery over the long term, and ways these factors may be mitigated. Chapter 4 provides a brief summary of the research and future research needs.

Chapters are presented in paper format so that they may be read and interpreted independently. Thus, some duplication of treatment and site descriptions, figures and tables occur. Maintaining the stand alone format, literature cited appears specific to each chapter at the end of each chapter. References are conglomerated at the end of the thesis as per University of Alberta thesis requirements.

9. LITERATURE CITED

Alberta Agriculture and Forestry. 2015. Alberta rangelands in range and pasture management. Alberta Agriculture and Forestry. On line at http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag2111. Accessed 20 June 2016.

Alberta Geological Survey. 2013. Alberta Oil Sands. Onn line at http://www.ags.gov.ab.ca/energy/oilsands/index.html. Accessed 12 September 2014.

Alberta Transportation. 2013. Alberta transportation guide to reclaiming borrow excavations. On line at http://www.transportation.alberta.ca/Content/DocType245/Production/borrowguide.pdf. Accessed 8 December 2014.

Amaranthus, MP, DS Parrish and DA Perry. 1989. Decaying logs as moisture reservoirs after drought and wildfire. Pp 191-194. In: EB Alexander (ed). Proceedings of Watershed 89 a Conference on the Stewardship of Soil, Air, and Water Resources. United States Department of Agriculture, Forest Service Alaska Region. Juneau Alaska.

Archibold, OW, C Acton and EA Ripley. 2000. Effect of site preparation on soil properties and vegetation cover and the growth and survival of white spruce *(Picea glauca)* seedlings, in Saskatchewan. Forest Ecology and Management 131:127-141.

Bachmann, S, VJ Lieffers and SM Ländhausser. 2015. Forest floor protection during drilling pad construction promotes resprouting of aspen. Ecological Engineering 75:9-15.

Beach, EW and CB Halpern. 2001. Controls on conifer regeneration in managed riparian forests: effects of seed source, substrate, and vegetation. Canadian Journal of Forest Research 31:471-482.

Beckingham, JD and JH Archibald, 1996. Field guide to ecosites of northern Alberta. Natural Resources Canada, Canadian Forest Service, Northwest Region, Northern Forestry Centre. Edmonton Alberta. Special Report 5.

Boateng, JO, JL Heineman, J McClarnon and L Bedford. 2006. Twenty year responses of white spruce to mechanical site preparation and early chemical release in boreal region of northeastern British Columbia. Canadian Journal of Forest Research 36:2386-2399.

Bergeron, Y, HYH Chen, NC Kenkel, AL Leduc and SE Macdonald. 2014. Boreal mixedwood stand dynamics: ecological processes underlying multiple pathways. The Forestry Chronicle 90:202-213.

Bonan, GB and HH Shugart. 1989. Environmental factors and ecological processes in boreal forests. Annual Review of Ecology and Systematics 20:1-28.

Boyle, TJB. 1992. Biodiversity of Canadian forests - current status and future challenges. Forestry Chronicle 68:444-453.

Brady, NC and RR Weil. 2010. Elements of the nature and properties of soils. Prentice Hall. New Jersey United States of America. 614 pp.

Brandner, TA, RO Pererson and KL Risenhoover. 1990. Balsam fir on Isle Royale – effects of moose herbivory and population density. Ecology 71:155-164.

Brandt, JP, MP Flannigan, DG Maynard, ID Thompson and WJA Volney. 2013. An introduction to Canada's boreal zone: ecosystem processes, health, sustainability, and environmental issues. Environmental Review 21:207-226.

Brown, RL and MA Naeth 2014. Woody debris amendment enhances reclamation after oil sands mining in Alberta, Canada. Restoration Ecology 22:40-48.

Burton, PJ, C Messier, DW Smith and WL Adamowicz (eds). 2003. Towards sustainable management of boreal forest. NRC Research Press. Ottawa Ontario Canada. 1039 pp.

Canadian Association of Petroleum Producers(CAPP). 2014. What are oil sands? On line at http://www.capp.ca/CANADAINDUSTRY/OILSANDS/ENERGY-ECONOMY/Pages/what-are-oilsands.aspx. Accessed 3 October 2014.

Christy, EJ and RN Mack. 1984. Variation in demography of juvenile *Tsuga heterophyla* across the substratum mosaic. Journal of Ecology 72:75-91.

Conlin, TSS. 2001. In-woods chipping: possible evidence for allelochemical interaction of leachate generated from trembling aspen (*Populus tremuloides* Michx.) bark and wood waste. Forestry Chronicle 77:345-349.

Cooke, BJ and J Roland. 2007. Trembling aspen responses to drought and defoliation by forest tent caterpillar and reconstruction of recent outbreaks in Ontario. Canadian Journal of Forest Research 37:1586-1598.

Corns, IGW. 1987. Compaction by forestry equipment and effects on coniferous seedling growth on four soils in Alberta foothills. Canadian Journal of Forest Research 18:75-84.

Corns, IGW and DG Maynard. 1998. Effects of soil compaction and chipped aspen residue on aspen regeneration and soil nutrients. Canadian Journal of Soil Science 78:85-92.

Curzon, MT, AW D'Amato and BJ Palik. 2014. Harvest residue removal and soil compaction impact forest productivity and recovery: potential implications for bioenergy harvests. Forest Ecology and Management 329:99-107.

Day, RJ. 1972. Stand structure, succession and use of southern Alberta's Rocky Mountain Forest. Ecology 53:472-478.

De Grandpré, L, D Gagnon and GD Bergeron. 1993. Changes in the understory of Canadian southern boreal forest after fire. Journal of Vegetation Science 4:803-810.

Duan, M, J House and SX Chang. 2015. Limiting factors for lodgepole pine (*Pinus contorta*) and white spruce (*Picea glauca*) growth differ in some reconstructed sites in the Athabasca oil sands region. Ecological Engineering 75:323-331.

Eis, S. 1967. Establishment and early development of white spruce in the interior of British Columbia. Forestry Chronicle 43:174-177.

Environment and Sustainable Resource Development (ESRD). 2009. Management of wood chips on public land. Lands Division, Land Management Branch, Petroleum Land Use and Reclamation Section, Government of Alberta. Industry Directive Number: ID 2009-01. Edmonton Alberta. 2 pp.

Environment and Sustainable Resource Development (ESRD) 2013. 2010 Reclamation criteria for wellsites and associated facilities for forested lands (Updated July 2013). Edmonton Alberta. 81 pp.

Forest Research Advisory Council of Canada. 1994. Forest research priorities in Canada, 1993. Forestry Chronicle 70:84-87.

Franklin, CMA and KA Harper. 2016. Moose browsing, understorey structure and plant species composition across spruce budworm-induced forest edges. Journal of vegetation Science 27:524-534.

Gärtner, SM, VJ Lieffers and SE Macdonald. 2011. Ecology and management of white spruce in the boreal forest. National Research Council. Environmental Review 19:461-478.

Ghose, MK. 2001. Management of topsoil for geoenvironmental reclamation of coal mining areas. Environmental Geology 40:1405-1410.

Global Forest Watch Canada (2005). 2005 natural regions and Subregions of Alberta [map]. Scale not given. In: Maps – the last great intact forest landscapes of Canada: Atlas of Alberta: Part 1. On line at http://global forestwatch.ca/publications/20090402A_MapsI. Accessed 15 December 2016.

Government of Alberta. 2007. Forest and prairie protection act: the forest and prairie protection regulations. Part II. Alberta regulation 310/1972. Alberta Queen's Printer. Edmonton Alberta. 12 p.

Government of Alberta. 2011. Reclamation of specified land; 2010 reclamation criteria (Updated June 2011). On line at http://environment.alberta.ca/documents/2010-Reclamation-Criteria-Fact-Sheet.pdf. Accessed 20 September 2014.

Government of Alberta. 2013. Alberta oil sands industry quarterly update, summer 2013. On line at https://albertacanada.com/files/albertacanada/AOSIDQuarterly_Update_Summer2013. pdf. Accessed October 3, 2014.

Government of Alberta. 2014. Alberta Regulation 115/1993, environmental protection and enhancement act, conservation and reclamation regulation. Office Consolidation. Alberta Queen's Printer. Edmonton Alberta.

Government of Alberta. 2016. Vegetation inventory standards. Alberta Agriculture and Forestry. On line at http://www.agric.gov.ab.ca/app21/forestrypage?cat Forest%20Management. Accessed 2 August 2016.

Gradowski, T, D Sidders, T Keddy, VJ Lieffers and SM Landhäusser. 2008. Effects of overstory retention and site preparation on growth of planted white spruce seedlings in deciduous and coniferous dominated boreal plains mixedwoods. Forest Ecology and Management 255:3744-3749.

Grime, JP. 1979. Plant strategies and vegetation processes. John Wiley and Sons. Chichester New York. Pp 183.

Greene, DF, JC Zasada, L Sirois, D Kneeshaw, H Morin, I Charron and MJ Simard. 1999. A review of regeneration dynamics of North American boreal forest tree species. Canadian Journal of Forest Research 29:824-839.

Grover G and W Fast. 2007. Alberta making strides in mixedwood management. Forestry Chronicle 83:714-718.

Harmon, ME, JF Franklin, FJ Swanson, P Sollins, SV Gregory, JD Lattin, NH Anderson, SP Cline, NG Aumen, J Sedell, GW Lienkaemper, K Cromack Jr. and KW Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133-302.

Hart, SA and HYH Chen. 2006. Understory vegetation dynamics of North American boreal forests. Critical Reviews in Plant Sciences 25:381-397.

Hassan, R, R Scholes and N Ash (eds). 2005. Ecosystems and human wellbeing: current state and trends. Vol. 1. Millennium ecosystem assessment series. Island Press. London, United Kingdom. 948 pp.

Jean, PO, RL Bradley and JP Tremblay. 2015. Testing for bottom-up effects in an overbrowsed boreal landscape. Wildlife Biology 21:318-322.

Johnson, EA and K Miyanishi. 2007. Disturbance and succession. In: Plant disturbance ecology: the process and the response. Academic Press. Burlington Massachusetts. Pp 1-14.

Kabzems, R. 2012. Aspen and white spruce productivity is reduced by organic matter removal and soil compaction. Forestry Chronicle 88:306-316.

Kenkel, NC, DJ Walker, PR Watson, RT Caners and RA Lastra. 1997. Vegetation dynamics in boreal forest ecosystems. Coenoses 12:97-108.

Kneeshaw, D, Y Bergeron and T Kuuluvainen. 2011. Forest ecosystem structure and disturbance dynamics across the circumboreal forest. In: A Millington, M Blumler and U Schickhoff (eds). The SAGE handbook of biogeography. SAGE Publications. London United Kingdom. Pp 261-278.

Kuuluvainen, T. 2002. Natural variability of forests as a reference for restoring and managing biological diversity in boreal Fennoscandia. Silva Fennica 36:97-125.

Koroleff, A, 1954. Leaf litter as a killer. Journal of Forestry 52:178-182.

Kreutzweiser, D, F Beall, K Webster, D Thompson and I Creed. 2013. Impacts and prognosis of natural resource development on aquatic biodiversity in Canada's boreal zone. Environmental Review 21:227-259.

Landhäusser, SM and VJ Lieffers. 2001. Photosynthesis and carbon allocation of six boreal tree species grown in understory and open conditions. Tree Physiology 21:241-248.

Landhäusser, SM, VJ Lieffers and P Chow. 2007. Impact of chipping residues and its leachate on the initiation and growth of aspen root suckers. Canadian Journal of Soil Science 87:361-367.

LaRoi, GH and MHL Stringer. 1976. Ecological studies in the boreal spruce-fir forests of the North American taiga, II. Analysis of the bryophyte flora. Canadian Journal of Botany 54:619-643.

Lieffers, VJ, SE Macdonald and EH Hogg. 1993. Ecology of and control strategies for *Calamagrostis canadensis* in boreal forest sites, Canadian Journal of Forest Research 23:2070-2077.

Lieffers, VJ, KJ Stadt and S Navratil. 1996. Age structure and growth of understory white spruce under aspen. Canadian Journal of forest Research 26:1002-1007.

Lupi, C, H Morin, A Deslauriers, S Rossi and D Houle. 2013. The role of soil nitrogen for the conifers of the boreal forest: a critical review. International Journal of Plant and Soil Science 2:155-189.

MacDonald, GB. 1995. The case for boreal mixedwood management: an Ontario perspective. The Forestry Chronicle 71:725-734.

Mackenzie, DD. 2013. Oil sands mine reclamation using boreal forest surface soil (LFH) in northern Alberta. PhD dissertation. Department of Renewable Resources, University of Alberta. Edmonton Alberta. 240 pp.

Mallik, AU and D Hu. 1997. Soil respiration following site preparation treatments in boreal mixedwood forest. Forest Ecology and Management 97:265-275.

Michaelian, M, EH Hogg RJ Hall and E Arsenault. 2011. Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. Global Change Biology 17: 2084–2094.

Miller, JJ and D Curtin. 2008. Electrical conductivity and soluble ions. Pages 161-172 In MR Carter and EG Gregorich (eds). Soil sampling and methods of analysis. Canadian Society of Soil Science and CRC Press. Boca Raton Florida.

Miller MR and SW May. 1979. Below-ground ecosystems project. Pages 64-70 In: Land Reclamation Program, Annual Report. 1978. Argonne National Laboratory, United States Department of Agriculture.

Molles Jr, MC. 2002. Ecology: concepts and applications. McGraw-Hill. New York, New York. Pp. 37-38.

Morris, DM and GB MacDonald. 1991. Development of a competition index for young conifer plantations established on boreal mixedwood sites. Forestry Chronicle 67:403-410.

Munson, AD, HA Margolis and DG Brand. 1993. Intensive silvicultural treatment: impacts on soil fertility and planted conifer response. Soil Science Society of America Journal 57:246-255.

Naeth, MA, R Brown and S Wilkinson. 2012. Use of woody debris as an amendment for reclamation after oil sands mining. Prepared for Canadian Oil Sands Network for Research and Development (CONRAD). Edmonton Alberta. 34pp.

Natural Regions Committee 2006. Natural regions and subregions of Alberta. Compiled by DJ Downing and WW Pettapiece. Government of Alberta. Pub. No. T/852. Edmonton Alberta.
Nguyen-Xuan, T, Y Bergeron, D Simard, JW Fyles and D Pare. 2000. The importance of forest floor disturbance in the early regeneration patterns of the boreal forest of western and central Quebec: a wildfire versus logging comparison. Canadian Journal of Forest Research 30:1353-1364.
Nienstaedt, H and JC Zasada. 1990. *Picea glauca* (Moench) Voss - White spruce, In: Silvics of North America: 1. Conifers, Agriculture Handbook No. 654, United States Department of Agriculture and Forest Service. Washington District of Columbia. Pp. 204-225.
Nishi, JS, S Berryman, JB Stelfox, A Garibaldi and J Straker. 2013. Fort McKay cumulative effects project: technical report of scenario modeling analyses with ALCES®. ALCES Landscape and Land Use. Calgary Alberta. Integral Ecology Group. Victoria British Columbia. Prepared for the Fort McKay Sustainability Department. Fort McMurray Alberta. 126 pp + 5.
Oil Sands Vegetation Reclamation Committee. 1998. Guidelines for reclamation to forest vegetation in the Athabasca oil sands region. First edition. ISBN 0-7785-0411-5. Alberta Environment Protection. Edmonton Alberta.
Osko, T. 2016. Personal communication. University of Alberta, Edmonton.
Osko, T and M Glasgow. 2010. Removing the wellsite footprint: recommended practices for construction and reclamation of wellsites on upland forests in boreal Alberta. Department of Biological Sciences, University of Alberta. Edmonton Alberta.
Pastor, J and RJ Naiman. 1992. Selective foraging and ecosystem processes in boreal forests. The American Naturalist 39:690-705.
Peters, VS, SE Macdonald and RT Dale. 2006. Patterns of initial versus delayed regeneration of white spruce in boreal mixedwood succession. Canadian Journal of Forest Research 36:1597-1609.
Petroleum Geoscience Society. 2012. The Athabasca oil sands formation in the Lyell Collection of the Geological Society of London. On line at http://pgc.lyellcollection.org/content/ 7/1141 /F1.expansion.html. Accessed 12 October 2015.
Potvin, F, P Beaupre and G. Laprise. 2003. The eradication of balsam fir stands by white-tailed deer on Anticosti Island, Québec : a 150-year process. Ecoscience 10:487-495.
Powter, C, N Chymko, G Dinwoodie, D Howat, A Janz, R Puhlmann, T Richens, D Watson, H Sinton, K Ball, A Etmanski, B Patterson, L Brocke and R Dyer. 2012. Regulatory history of Alberta's industrial land conservation and reclamation program. Canadian Journal of Soil Science 92:39-51.
Purdy, BG, SE Macdonald and MRT Dale. 2002. The regeneration niche of white spruce following fire in the mixedwood boreal forest. Silva Fennica 36:289-306.
Renkema, KN, VJ Lieffers and SM Ländhausser. 2009. Aspen regeneration on log decking areas as influenced by season and duration of log storage. New Forests 38:323-335.
Rosell, F, O Bozsér, P Collen and H Parker. 2005. Ecological impact of beaver *Castor fiber* and *Castor canadensis* and their ability to modify ecosystems. Mammal Review 35:248-276.
Rowe, JS. 1972. Forest regions of Canada. Fisheries and Environment Canada, Canadian Forest Service. Publication No.1300. Ottawa Ontario.
Schneider, R and S Dyer. 2006. Death by a thousand cuts; impacts of in situ oil sands development on Alberta's boreal forest. The Pembina Institute and Canadian Parks and Wilderness Society. Edmonton Alberta. ISBN 0-921719-83-3, 1st ed. 1:0-06-07-18.
Soil Classification Working Group. 1998. The Canadian system of soil classification. Agriculture and Agri-Food Canada. Publication number 1646 (Revised). 187 pp.
Startsev, AD and DH McNabb. 2007. Effects of compaction on aeration and morphology of boreal forest soils in Alberta, Canada. Canadian Journal of Soil Science 89:45-56.

Stone, DM and JD Elioff. 1998. Soil properties and aspen development five years after compaction and forest floor removal. Canadian Journal of Soil Science 78:51-58.

Straker, J and G Donald. 2011. Assessing re-establishment of functional forest ecosystems on reclaimed oil sands mine lands. On line at https://circle.Ubc.ca/bitstream/handle/2429/42303/Straker_J_et_al_BC2_Mine.pdf?sequence=1. Accessed 20 September 2014.

Suffling, R, C Lihou and Y Morand. 1988. Control of landscape diversity by catastrophic disturbance: a theory and a case study of fire in a Canadian boreal forest. Environmental Management 12:73-78.

Sutton, RF. 1969. Silvics of white spruce (*Picea glauca* (Moench) Voss). Canadian Forestry Service. Publication 1250. Ottawa, ON. 57 pp.

United States Department of Agriculture (USDA). 2003. Quaking aspen *Populus tremuloides* Michx. In: Plant guide. United States Department of Agriculture and Natural Resources Conservation Service. On line at https://plants.usda.gov/plantguide/pdf/cs_potr5.pdf. Accessed 5 June 2016.

Venier, LA, ID Thompson, R Fleming, J Malcolm, I Aubin, JA Trofymow, D Langor, R Sturrock, C Patry, RO Outerbridge, SB Holmes, S Haeussler, L De Grandpré, HYH Chen, E Bayne, A Arsenault and JP Brandt. 2014. Effects of natural resource development on the terrestrial biodiversity of Canadian boreal forests. Environmental Review 22:457-490.

Vinge, T and M Pyper. 2012. Managing woody materials on industrial sites. Alberta School of Forest Science and Management, University of Alberta. Edmonton Alberta.

Visser, S, J Fujikawa, CL Griffiths and D Parkinson. 1984. Effect of topsoil storage on microbial activity primary production and decomposition potential. Plant and Soil 82:41-50.

Waldron, RM 1966. Factors affecting natural white spruce regeneration on prepared seedbeds at the Riding Mountain Forest Experimental Area, Manitoba. Government of Canada, Department of Forestry and Rural Development, Forest Research Laboratory. Winnipeg Manitoba. Departmental publication 1169. 48 pp.

Wang, GG and K Klinka. 1996. Classification of moisture and aeration regimes in sub-boreal forest soils. Environmental Monitoring and Assessment 39:451-469.

Weber, MG and BJ Stocks. 1998. Forest fires and Sustainability in the Boreal Forests of Canada. Ambio 27:545-550.

Wikipedia. 2014. History of the petroleum industry in Canada (oil sands and heavy oil). On line at http://en.wikipedia.org/wiki/History_of_the_petroleum_industry_in_Canada_ (oil_sands_ and_heavy_oil). Accessed September 10, 2014.

Zackrisson, O. 1977. Influence of forest fires on north Swedish boreal forest. Oikos 29:22-32.

Zasada, JC and RA Gregory. 1969. Regeneration of white spruce with reference to interior Alaska: a literature review. United States Department of Agriculture and Forest Service Research Paper PNW-79. Pacific Northwest forest and Range Experiment Station, Institute of Northern Forestry, and United States Department of Agriculture. Juneau Alaska. 37 pp.

Table 1.1. Fire adapted regeneration response of common boreal tree species adapted from Kneeshaw et al (2011).

Species	Adaptation	Shade Tolerance
Jack pine	Serotinous cones	Intolerant
Lodgepole pine	Serotinous cones	Intolerant
Balsam fir	Wind dispersal, layering	Very tolerant
White spruce	Wind dispersal, masting	Moderate
Tamarack	Wind dispersal	Intolerant
Trembling aspen	Root suckering, wind dispersal	Intolerant
Balsam poplar	Root suckering, wind dispersal	Intolerant
Paper birch	Wind dispersal	Intolerant

Table 1.2. 2010 Reclamation criteria fact sheet adapted from Government of Alberta 2011.

Parameter	Cultivated Lands	Native Grasslands	Forested Lands
Landscape			
Drainage	Onsite and offsite drainage patterns must be comparable		
Erosion	Onsite and offsite erosion patterns must be comparable (gullies, blowouts, etc.)		
Stability	Onsite and offsite stability patterns stability must be comparable (slope movement, slumping, subsidence, etc.)		
Bare Areas	Onsite bare areas must be comparable to offsite bare areas		
Contour	Contours onsite must be comparable to contours offsite		
Amendments	A two year waiting period, after amendment application is required before an assessment can be conducted		
Gravel and rocks	Must not impede operability		
Debris	Organic debris: should not impede operability; native grassland: excess organic debris can be removed; forested: coarse woody debris spread over the site and not piled, windrowed or concentrated in one area		
Soils			
Depth average	85% of control depth	80% of control depth	80% of control depth
Depth required	≥ lowest control measurement (LCM)	No criteria requirements	No criteria requirements
Depth minimum	80% of the LCM	No criteria requirements	No criteria requirements
Consistence, Structure, texture	Soil consistence, structure, and texture must be comparable to offsite		
Soil colour	Must be comparable to offsite	No criteria requirements	No criteria requirements
Rooting Restrictions	Rooting restrictions onsite must be comparable to rooting restrictions observed offsite		
OM, pH % clay	Soil pH, organic matter (OM), and texture (% clay) onsite must be comparable to offsite		
EC, SAR	Electrical conductivity (EC) and sodium adsorption ratio (SAR) onsite must be comparable to offsite		
Vegetation			
Species composition	Type and mix comparable with control species, or meet reasonable land management objectives (LMO)	Type and mix consistent with native species present and meet reasonable LMO Native plant community onsite 70% of control community for undisturbed sites, 50% for disturbed sites	Type and mix consistent with native species present and meet reasonable LMO Natural recovery: stem count of 5 Planted sites: stem count of 2 for merchantable seedlings
Plant height	Average: 85% of control average	No criteria requirements	No criteria requirements
Plant density	Required: ≥ the LCM Minimum: 80% of the LCM		
Litter	No criteria requirements	Undisturbed sites: ≥ 65% of litter threshold value Disturbed sites: : ≥ 15% of litter threshold value	No criteria requirements
Plant health	Plants should be healthy, signs of stress onsite should be comparable to those observed offsite		
Plant health	Plants should be healthy, signs of stress onsite should be comparable to those observed offsite		No criteria requirements
Weeds	Weeds present (composition and distribution) onsite must be comparable to offsite Weeds must be managed as per weed control act; restricted weeds destroyed and noxious weeds controlled. Must not impede landowner operability		

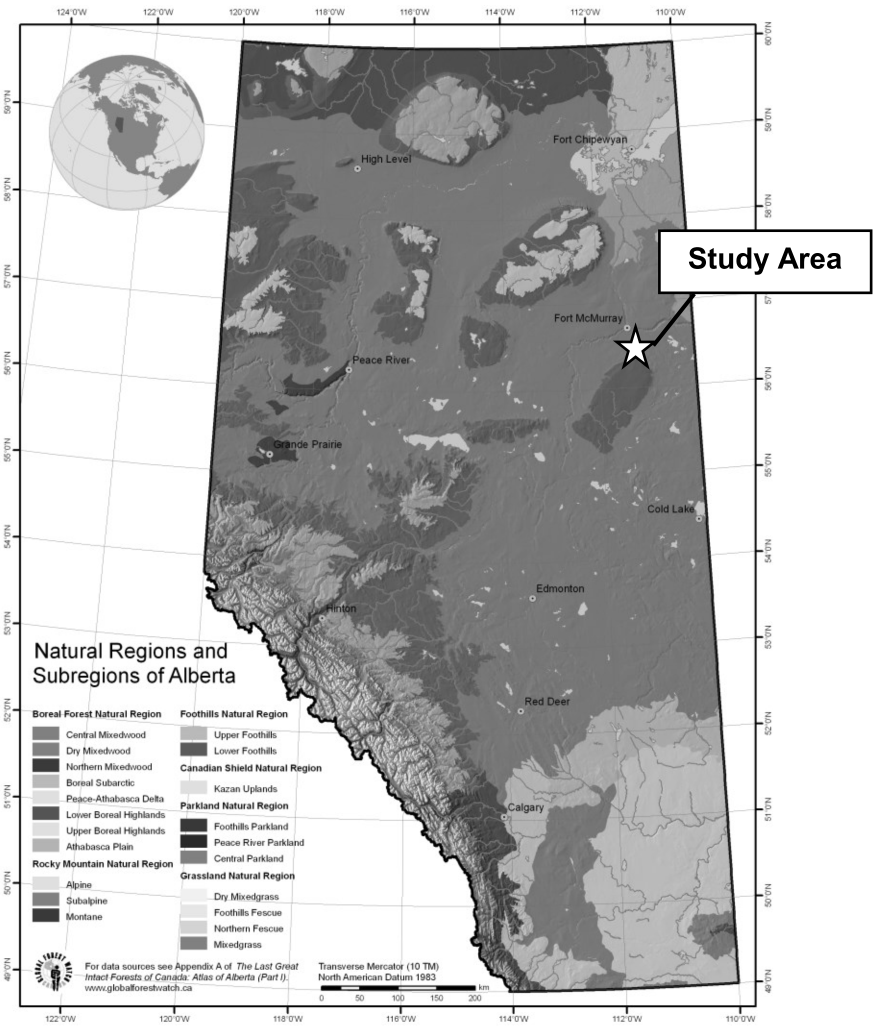

Figure 1.1. The natural subregions of Alberta, adapted from Global Forest Watch Canada (2005).

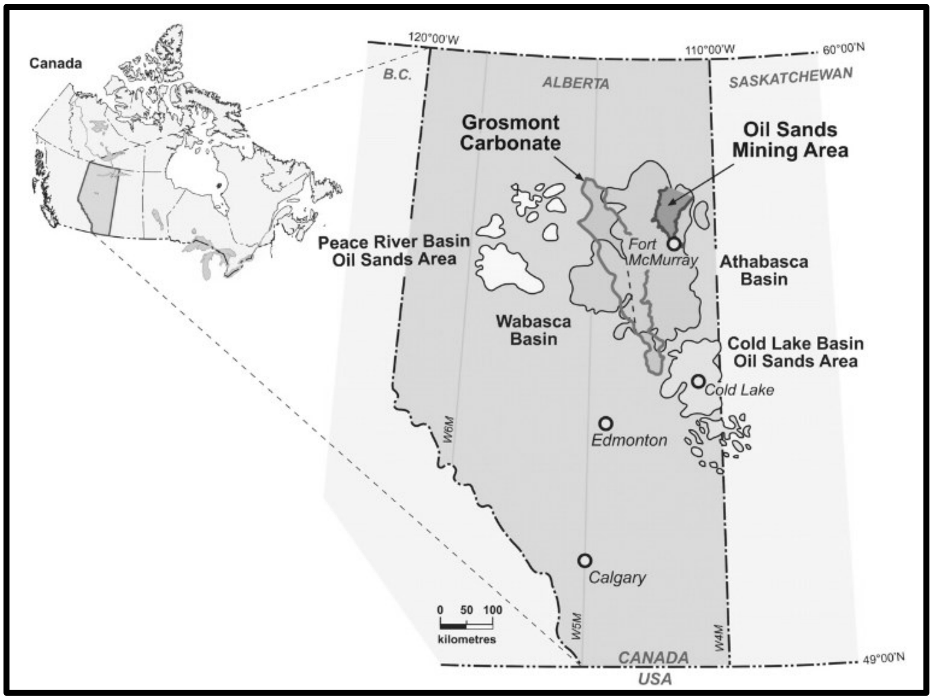

Figure 1.2. The Athabasca Oil Sands Formation adapted from the Petroleum Geoscience Society (2012).

CHAPTER II: EFFECTS OF WELL SITE MANAGEMENT ON LONG TERM VEGETATION RECOVERY WITHIN BOREAL FOREST

1. INTRODUCTION

Factors that contribute to poor ecological recovery on upland sites exposed to boreal oil sands exploration and development in northeastern Alberta, Canada, may be mitigated during construction and/or reclamation. While current reclamation practices are often considered insufficient for boreal forest recovery (eg Schneider and Dyer 2006), industry is continuing development at what some consider an ecologically unsustainable level, resulting in ongoing forest quality decline and impaired ecological function over the long term (Nishi et al 2013).

The boreal forest is a circumpolar ecosystem covering 11 % of the earth's surface (Bonan and Shugart 1989) with broad economic and ecological importance. Boreal forest is an important source of timber and fresh water, plays a key role in global climate regulation and hydrologic cycling (Hassan et al 2005), is critical habitat for many aquatic and terrestrial species (Venier et al 2014, Kreutzweiser et al 2013) and has cultural value for many peoples (Hassan et al 2005). Alberta boreal forest covers more than 50 % of the province, of which half is within the boreal mixedwood (Figure 2.1) (Natural Regions Committee 2006).

Boreal forest is a mosaic of vegetation patches expressing variable plant species richness and composition as a direct reflection of site hydrologic regime, nutrient and light availability and disturbance history (Bergeron et al 2014, Beckingham and Archibald 1996, Bonan and Shugart 1989). A major component of well site vegetation recovery is regeneration of plant communities from surviving vegetation, seed banks and buried propagules; these components vary with site disturbance history, including type, frequency and intensity. Historically, fire has been the most common and influential disturbance in boreal forest, shaping adaptive responses of ruderal, competitive and stress tolerant species. These responses, combined with relative abundance of propagules present, post-disturbance ecosite, weather and growing conditions, determine which plant species establish and which are eliminated or emerge through subsequent successional development. Soil management in construction, storage and reclamation phases of a well site directly impact plant propagule survival, and therefore vegetation recovery.

Little is known about long term effects of surface well disturbances on regeneration of boreal forest plant communities. These well sites are small but abundant, creating numerous disturbances across a large area to which spatial and temporal access is limited (mostly to winter months). Thus reclamation targets must be clear and techniques efficient during construction and reclamation. Re-entering well sites at a later date to amend a reclamation project generates further disturbance, slows and delays recovery and is financially undesirable.

2. RESEARCH OBJECTIVES

This research was conducted to identify factors that contribute to successful revegetation of upland well sites in Alberta boreal forest to develop best management practices during construction and reclamation. Success is defined as identifying factors that contribute to greater (and more rapid) vegetation successional development convergent with the surrounding forest, including factors that promote regeneration of native plant communities. A-priori use of well site treatments allowed for direct comparison of conventional methods with alternative construction and revegetation methods thought to reduce impacts on existing vegetation, remaining plant propagules and associated soil. The following specific objectives were addressed.

- To assess how similar plant communities on nine to ten year old well sites with different treatments were to their associated forest controls, and how similar treatment community characteristics were to forests recovering from post-harvest disturbance (cutblocks). To determine whether disturbances changed revegetation patterns of recovering forest, and to identify treatments that caused more or less change to early successional plant communities.
- To assess effects of soil disturbance on plant communities developing on well sites constructed with low disturbance (iced-in with no soil excavation), high disturbance (conventional soil stripping), duff stripping and root salvage techniques. Low disturbance, duff stripping and root salvage sites were compared with conventional soil stripping sites to determine if these methods had less impact on plant communities.
- To assess soil disturbance and effect of soil storage methods on plant communities, two soil and debris piling treatments were studied at excavated sites. Soil storage included piling in a single progressive pile (one layer on top the other) or in separate piles.
- To assess effects of woody debris type and distribution in reclamation on plant communities. On conventional sites coarse woody materials were evenly spread across the soil surface or spread on half the site and windrowed on the other. On low disturbance sites woody materials were spread as whole slash on half the site and windrowed on the other, or mulched and spread across the site. Deep versus shallow mulching effects were assessed.
- To assess effects of initial tree planting on plant communities (all but root salvage sites were planted with 150 to 200 trees on a random half of the site).

3. METHODS

3.1. Research Site Descriptions

Research sites were in boreal forest near Anzac, Alberta (Figure 2.1) in the Central Mixedwood Natural Subregion (Global Forest Watch Canada 2006). Sites span 40 km from Townships 82 to 86, between Ranges 6 and 8, west of the 4th Meridian. The region is characterized by gently rolling to hummocky moraine receding to lacustrine flats underlain by Cretaceous shales (Natural Regions Committee 2006, Rowe 1972). Sites were mid to late seral forest prior to the current disturbances, with mesic to sub-mesic *Populus tremuloides* Michx (trembling aspen) or aspen - *Picea glauca* (Moench) Voss (white spruce) mixtures in variable proportions on Gray Luvisolic soils of varying texture. Ecotypic understory components ranged from *Viburnum edule* (Michx) Raf (low bush cranberry), *Rosa acicularis* Lindl (prickly wild rose), *Alnus crispa* (Chaix) DC (green alder) or *Cornus sericea* L (red osier dogwood), to *Ledum groenlandicum* Oeder (Labrador tea), Ericaceous shrubs and feather mosses (Table A.1, Appendix A).

3.2. Experimental Design, Treatments And Plot Establishment

Thirty-three well sites selected for research were developed for oil sands exploration between 2004 and 2006 and reclaimed during winter months using different soil handling and woody debris management methods (Table 2.1). Each treatment group consisted of two to three well sites, with each site combining soil and woody debris management treatments. Well sites were mostly 70 x 70 m in size; one root salvage site was 70 x 90 m and two sites were 70 x 100 m. Four plots were established in each treatment at each site. Plots established in 2004 were 10 x 10 m; those established in 2005 and 2006 were 12 x 12 m. The exception was mulch depth treatments, which had three 3 x 3 m plots in each treatment at each site (Figure 2.2).

Except for six root salvage sites, whose excavation method was designed to examine natural tree regeneration, all sites were planted in early summer following site decommissioning and soil replacement where excavation occurred; 150 to 200 trees were planted on a randomly selected half of the well site, thereby creating planted and non-planted treatments (Figure 2.2). Trees were planted at 2 m grid spacing, for an equivalent planting density of 3,300 trees per hectare. In 2004, alternating rows of trembling aspen, *Populus balsamifera* L (balsam poplar), and white spruce were planted. Sites reclaimed in 2005 and 2006 were planted with the same species, with *Betula papyrifera* Marshall (paper birch) incorporated between rows of aspen and spruce, still maintaining 2 m grid spacing.

Thirteen sites were constructed with a low disturbance (iced-in) method. Little soil disturbance occurred at these locations. Mulch, snow and ice were used to build a level construction platform during exploration. On eight of these, non-merchantable vegetation was mulched and spread at variable (non-specific) depths according to conventional debris management methods during reclamation. At three sites, mulch was spread to depths of ≤5 cm and ≥ 10 cm in alternating 10 m wide strips (hereafter shallow and deep mulch treatments, respectively). On the remaining two low disturbance sites, vegetation was left as whole (non-mulched) slash evenly spread on half of the site and windrowed on the other half.

Eleven sites were constructed and reclaimed using conventional practices. On five sites salvaged whole slash was evenly spread across the site. On six sites half of the site was windrowed and on the other half slash spread evenly at reclamation. During construction, soils were stripped by a dozer in two passes. The first pass removed LFH (organic) and the second removed underlying mineral Ae horizon, usually with some B horizon when the Ae was < 15 cm depth. Stripped soils were stored at the edge of the site, for three to four months, then replaced during reclamation.

Three sites with single (progressive) soil piles were selected to compare to three sites with separated piles. Site space limitations occasionally required one progressive pile, with slash on the bottom, then LFH, then surface soil and possibly B horizon. At the other three sites, soils were piled separately with LFH and A horizon in one pile, and B horizon in another, with the latter placed first during reclamation. Piling soils separately may be beneficial by reducing mixing of soil layers, thereby limiting alteration of physical and chemical properties of excavated soils, and preventing deep burial of seeds and propagules important for revegetation (Osko and Glasgow 2010). Attempts were made to replace all soils according to their originating depth, but it is likely more mixing of layers occurred in soils that were progressively piled.

Root salvage treatments were applied at the remaining six sites, and compared to five conventionally constructed sites established using progressive soil piles. Conventional two-pass stripping is often performed using soil colour as an indicator of stripping depth. Aspen roots are mostly located where a soil colour change occurs at the LFH and Ae interface (Osko and Glasgow 2010). The first pass in with root salvage excavated at a greater depth to prevent root damage by equipment; during subsequent storage, aspen roots were bound within larger soil aggregates than with conventional stripping. A second pass including lower Ae and some B horizon was performed where needed to level prior to construction, with soils piled separately.

Three study sites were constructed with a duff stripping method, removing only the LFH layer and occasionally a small amount of mineral A horizon. These sites were compared to low disturbance sites treated with mulch, and conventional sites treated with spread slash to determine if duff stripping provided reduced disturbance and more favourable vegetation recovery relative to the two-pass stripping.

3.3. Vegetation Assessment

In 2014, natural revegetation success was assessed for sites reclaimed in 2004 and 2005. Sites in Townships 84 to 86 were assessed July 14 to 28. Sites in Township 82 and cutblocks (Township 85) were assessed August 4 to 13. Sites reclaimed in 2006 were evaluated in 2015; sites in Township 84 were assessed July 27 to August 18, sites in Townships 82 and 83 were assessed August 13 to 16. All plant nomenclature and identification followed Moss (1983), Johnson et al (2009) and Tannas (2003). All plants were identified to species except *Salicaceae* (*Salix* sp*,* willows) and *Cyperaceae* (*Carex* sp, sedges) were identified to genus, and some *Orchidaceae* (orchids) not in flower were identified to family to maximize field efficiency. Structure, species richness and diversity were determined. Ground cover components, bare soil, litter, woody debris, moss and lichen, were visually estimated (total 100 %).

At each site, vegetation and ground cover were assessed in each treatment plot. Five 1 x 1 m quadrats were randomly located in each plot for a total of 20 per treatment type (n=12 plots for each deep and shallow mulch treatment). For sites with a single woody debris treatment (mulched or spread whole slash), transects were established from one corner of a reference plot to the opposite corner, approximating a north-westerly direction. For sites with half spread and half windrowed woody material, transects radiated from centre as maintaining orientation in dense vegetation was difficult. Transects therefore crossed through shaded and brighter portions of each plot (if situated at site edge), and for plots with windrows, crossed the latter.

At each site, offsite (control) transects were established approximately 25 to 30 m from all four site edges. Five 1 x 1 m quadrats were located 15 to 20 m apart along each transect using stratified random sampling. Areas visually subject to other disturbances (recreational trail use, recent windthrow gaps) were avoided. Areas that were clearly lowland or riparian ecotypes were avoided, thereby limiting sampling to uplands. A total of 20 quadrats (12 for deep and shallow mulch treatment sites) were assessed within each site’s non-disturbed forest.

Cutblocks were sampled with a similar method. Transects were established approximately 20 m from cutblock edges. At each cutblock, one transect was established in a northerly direction, then easterly, southerly and westerly. Five 1 x 1 m quadrats were located 15 to 20 m apart along each transect using stratified random sampling. Areas that were visually disturbed since harvest were avoided (recreational vehicle use). Similarly, areas that were clearly lowland or riparian ecotype were avoided. A total of 20 quadrats were assessed per cutblock.

At one root salvage site, a vast distance of surrounding vegetation had been removed in 2009 or 2010 to create a firebreak for a nearby processing facility, leaving no nearby upland forest. The surrounding area was sampled, but could not be used as a control to assess similarity of the site to undisturbed forest, and therefore was excluded from analyses.

3.4. Statistical Analyses

Two data groups were used to assess similarity of treatment plant communities and associated controls, and similarity of forest development within treatment communities to that after harvest. These data were used for between treatment comparisons. Analyses were performed using R v. 3.2.5 software (R Core Team 2016).

The first dataset to find treatment differences and compare treatment vegetation to cutblocks included ground cover (bare ground, slash, moss, litter), vegetation group cover (grass, forbs, shrubs, trees, ratio of trees to grass and shrubs), species richness, Shannon Weiner indices (native and non-native diversity) and Jaccard similarity index. Indices were as follow.

$\mathrm{SW} = -\sum_{i=1}^{R}[(pi) * \ln(pi)]$ where pi is the proportional representation of the *i*th species within the group *R*.

$Js = \frac{a}{a+b+c}$, where a is the number of species in sample A and sample B, b is the number of species only in sample A, and c is the number of species only in sample B.

Statistical methods for analyses of this dataset included PerMANOVA, contrasts and ANOVA of linear mixed effects with REML. Alpha was set at 0.10 due to small sample size. Where treatment interactions were detected, LSD tests were performed to identify differences between means, with a Bonferroni correction to control family wise error rate. All data were checked for normality and homoscedasticity prior to analysis; some transformations were made. Vegetation group cover values were transformed to square roots or fourth roots for comparing the whole dataset with MANOVA. Comparing individual variables between groups, percent moss and bare ground and Shannon Wiener non-native diversity usually required square or fourth root transformations. Where data could not be transformed to meet assumptions of parametric analysis, non-parametric methods were used, including Wilcoxon and Levene tests and permutational ANOVA. Where PerMANOVA was used, normality and homoscedasticity of data were not checked as permutational procedures normalize data and ensure variance equality. All means and standard errors shown in tables are based on original (non-transformed) data.

All sites were grouped by soil disturbance, and compared to cutblocks. Low disturbance sites treated with mulch and spread slash were grouped separately. For simplicity, deep and shallow mulch sites were not included. Cutblock communities were compared to treatment communities using permutational ANOVA to assess differences in vegetation characteristics and make inferences regarding degree of alteration due to disturbance type. Vegetation characteristics were then compared between pre-determined groups to determine relative treatment effects.

Deep and shallow mulch treatments were assessed as a nested split plot design; the high versus low disturbance treatment group and duff stripping sites were assessed with a split plot design. Groups for direct comparison of deep and shallow mulch, high versus low disturbance, and high and low disturbance versus duff stripping, were analyzed using two-way ANOVA.

Root salvage sites had only community observation for comparison and two-pass stripping sites had two observations due to root salvage sites having planted and non-planted treatments. Root salvage sites were thus compared with the unplanted portion of high disturbance sites with one-way ANOVA. Error due to site could not be tested in this comparison therefore PerMANOVA was used to evaluate differences in plant communities between treatments. Low disturbance sites with spread and windrowed slash treatments in a split plot design were compared to low disturbance sites treated with mulch using two-way ANOVA. Where soil piling methods were compared, sites were in a split-plot design and compared with two-way ANOVA (soil pile, wood and planting treatments) and two-way ANOVA (wood and planting treatments).

The second dataset included cover of individual plant species found in at all sites, including soil disturbance treatments, slash management treatments, soil piling treatments, planted and non-planted treatments and control plots for each site. This dataset was used to generate cluster diagrams and ordination plots using non-metric multi-dimensional scaling (NMDS) of species data transformed by Sorensen's distance. Cluster analysis and ordination plots were used to verify integrity of control groups and observe spatial relationships among treatments.

NMDS methods were from R packages vegan (Oksanen et al 2015) and labdsv (Roberts 2016); ordination plots were based on low stress values and vector fitting to indicator species analysis results. For final ordination plots, vectors were based on indicator species analysis results. Hierarchical clustering was performed using R packages labdsv and ape (Paradis et al 2004).

Sorensen's similarity was chosen as the most appropriate method for generation of matrices.

$Ss = \frac{2a}{2a+b+c}$ where a is number of species in both sample A and sample B, b is number of species in sample A only, c is number of species in sample B only.

Bray-Curtis distance method, although widely used in plant community studies, increases the importance of abundant species (Quinn and Keough 2011), which would undermine the purpose of this research which was examining community recovery, including more subtle plant species, making the selection of a binary method preferable. The popular Jaccard similarity method produced ordination plots with high stress and greater difficulty to interpret. Clusters generated with Jaccard matrices showed more unique control groups than clusters from Sorensen's similarity matrices; thus, interpretation with Sorensen's distance was considered beneficial with low sample sizes. Sorensen's distance produced ordination plots whose vectors were better explained by the subsequent indicator species analysis, relative to other distance methods.

Indicator species analysis was performed using indval and multipatt (De Cáceres et al 2010) functions from R packages labdsv and indicspecies (De Cáceres and Jansen 2015), respectively, with alpha set at 0.05. According to De Cáceres (2013), good indicator species are present as a result of particular localized conditions (biotic or abiotic), are present as evidence of a change in local conditions (eg response to a treatment) or can be used to predict presence or absence of other species or groups of species within a given area. All these characteristics were of interest in observing successional development in the current investigation.

The function indval calculates indicator species values as the product of relative average abundance and relative average frequency of species from site clusters (Roberts 2016). The function indval determines indicator species through clustering; values are calculated independent of other species using the following index (from Legendre and Legendre 1998).

$$\mathrm{A_{kj}} = \frac{\mathrm{Nindividuals_{kj}}}{\mathrm{Nindividuals_{+k}}}$$

$$\mathrm{B_{kj}} = \frac{\mathrm{Nsites_{kj}}}{\mathrm{Nsites_{k+}}}$$

$\mathrm{INDVAL_{kj}} = \mathrm{A_{kj}B_{kj}}$ where $\mathrm{Nindividuals_{kj}}$ is mean abundance of species j within sites in cluster k, $\mathrm{Nindividuals_{+k}}$ is sum of mean abundances of species j within clusters, $\mathrm{Nsites_{kj}}$ is number of sites within a given cluster (k) that species j is found, $\mathrm{Nsites_{k+}}$ is number of sites in that cluster.

The indicspecies package has permutational functions to perform associate species analyses. Indicator species represent the affinity of a species to a site group within partitioned groups of sites. R has functions that extend theoretical use of indicator species, (primarily the work of

Dufrêne, Legendre and De Cáceres).

Associate species values reflect species affinity between site groups. Groups are not partitioned, and association values are derived permutationally to find the strongest association of groups of sites to a species. This allows for detection of species positively associated to more than one group, and negatively associated to one or more groups; inferences of preference or avoidance and similarity or dissimilarity may be made (De Cáceres et al 2010). The p-values derived from permutation represent to what degree the associations are statistically significant.

An extension of the association function performs an indicator species analysis on the permuted data. It partitions permutated data into single site groups and assesses strength of associations to those groups, thereby generating indicator species from permuted data. This is particularly useful for small datasets. A detailed description of these functions is in De Cáceres et al (2010).

4. RESULTS

Resultant ellipses in the ordination show distinct treatment effects. Cutblocks appear most similarly situated to intact forest controls, followed by low disturbance sites treated with slash (iced-in sites). PerMANOVA results show that cutblocks and low disturbance sites treated with whole slash were similar to uncut forest ($p = 0.135$ and 0.167, respectively) (Table 2.2). Areas of low disturbance treated with mulch differed from forest control areas in composition, but not cutblocks. Low disturbance mulch plots generally had more overlap with well sites of greater soil disturbance (Figure 2.3). While both progressive and separately piled two-pass stripping treatment ellipses extended furthest from controls suggesting a greater impact on vegetation recovery, root salvage, and particularly iced-in sites with mulch, together with duff stripping treatments, resulted in an intermediate shift in community assemblages relative to both controls and more extensive soil removal. Based on PerMANOVA results, root salvage and duff stripping treatments, with both piling treatments, diverged in composition from both cutblocks and intact forest 9 to 10 years after reclamation.

Among all well site treatments, cutblocks and controls, there were 34 indicator plant species, though none for low disturbance sites with mulch (Table 2.3). The association function produced 28 groups and a long list of species likely influenced by random distribution of species within treatment areas rather than just treatments, not surprising with such a large dataset. Therefore, only indicator and associate species with $p \le 0.02$ are presented (Table 2.3). Some notable assignments were made of common species to associated treatment groups, some of which became barometers of disturbance in this study (Figure 2.4).

All treatment groups including cutblocks and excluding controls were associated with *Rubus idaeus* L (red raspberry), *Calamagrostis canadensis* (Michx) P Beauv (bluejoint), *Equisetum arvense* L (field horsetail), *E sylvaticum* L (woodland horsetail) and *Taraxacum officinale* FH Wigg (dandelion). All treatment groups not including cutblocks or controls were associated with *Salix* sp, *Populus balsamifera* and *Poa pratensis* L (Kentucky bluegrass). Forest controls, cutblocks and iced-in sites with slash were associated with *Viburnum edule* and *Linnea borealis* L. (twinflower) (Table 2.3, Figure 2.4).

Summary plant community and ground cover characteristics of treatment groups were compared to cutblocks (Table 2.4). Cutblock plant communities had lower shrub cover than most treatments, had less grass cover and litter but more slash. Tree cover and tree to grass and shrub ratio were highest in cutblocks and lower with high disturbance (Table 2.4). Mean treatment tree to grass shrub ratio was associated with cutblocks and low mulch (Figure 2.5). Overall, cover pattern shows a gradient of increasing recovery with decreasing soil disturbance (Table 2.4, Figure 2.3). The tree to grass shrub ratio in duff stripped well sites was lowest of all treatments, and therefore situated furthest from that of cutblocks in the resulting ordination (Figure 2.3). All treatments differed from cutblocks in tree to grass shrub ratio (lower), except low slash favoured a shift toward trees and away from grass and shrubs.

4.1. Effect Of Soil Disturbance On Vegetation Development

Low disturbance had greater tree cover ($p = 0.005$), greater tree to grass shrub ratio ($p = 0.001$), lower forb cover ($p = 0.005$) and greater total plant cover ($p = 0.003$) than high disturbance (Table 2.5). Aspen was an indicator species for forest controls associated with high and low disturbance (Table 2.6), but was only associated with controls for the high disturbance. Therefore, the onsite aspen population in low disturbance appeared to be high enough to lead to similar conditions to the associated controls. *Calamagrostis canadensis*, *Poa pratensis, Equisetum arvense* and *Equisetum sylvaticum* were exclusive indicators of high disturbance and were not associated with low disturbance. High disturbance well sites were also associated with *Taraxacum officinale,* while low disturbance sites were associated with *Populus balsamifera*.

Overall, duff stripping was more similar to high than low disturbance. When duff stripping was compared to low disturbance, nine of fourteen summary plant community characteristics were different, including tree cover and tree to grass shrub ratio; both were greater with low disturbance ($p = 0.019$ and 0.017, respectively) (Table 2.7). Relative to high disturbance, six of fourteen plant community characteristics were different from duff stripping, although tree cover and tree to grass shrub ratio did not differ (Table 2.8). In general, there was less grass cover in both low and high disturbance treatments ($p = 0.015$ and 0.017, respectively) than duff stripping, and greater shrub cover ($p = < 0.001$ and 0.011, respectively). Total cover ($p = < 0.001$ both treatments) and forb cover were greater with low and high disturbance relative to duff stripped areas ($p = 0.023$ and <0.001, respectively, Tables 2.7 and 2.8).

Duff stripping had greatest grass cover of all treatments, and greater grass cover than cutblocks ($p \leq 0.001$) (Table 2.4). Relative to high and low disturbances, three of six indicators for duff stripping were grasses, and three more grasses and *Carex* sp were associated with duff stripping (Table 2.9). Duff stripping and high disturbance shared four associate species; three were grasses. Duff stripping, low disturbance and forest controls were associated with *Populus tremuloides* (Table 2.9). Duff stripping had greater similarity to controls, and lower species diversity ($p = 0.001$, both variables) than high disturbance treatments (Table 2.8) and lower species diversity relative to the low disturbance treatment ($p = < 0.001$) (Table 2.7).

Relative to high disturbance, root salvage had greater species richness and similarity to forest controls ($p = 0.053$ and 0.068, respectively) (Table 2.10). Root salvage had greater shrub cover, surface litter and plant species richness than cutblocks ($p \leq 0.01$, 0.01 and 0.05), and greater species richness than other treatments (Table 2.4). *Populus balsamifera* was an indicator species for root salvage, and high disturbance indicators included *Equisetum sylvaticum* and *Epilobium glandulosum* (Table 2.11). Root salvage and high disturbance were associated with *Calamagrostis canadensis, Rubus idaeus, Salix* sp and two non-native species. High disturbance was associated with forest controls by two forbs; root salvage was associated with controls by four species including *Populus tremuloides* and *Picea glauca* (Table 2.11). Tree cover or tree to shrub grass ratio did not differ between treatments (Table 2.10).

4.2. Effect Of Soil Pile Management On Vegetation Development

Tree cover and tree to shrub grass ratio were lower in both progressive ($p \leq 0.01$ and 0.001, respectively) and separate soil pile treatments ($p \leq 0.05$, both variables) relative to cutblocks (Table 2.4). Shrub cover was greater in progressive ($p \leq 0.01$) and separate pile ($p \leq 0.001$) treatments relative to cutblocks.

Between piling treatments, bare ground and forb cover were greater ($p = 0.026$ and 0.012, respectively) and tree to grass shrub ratio was greater ($p = 0.056$) with progressive rather than separate soil piling (Table 2.12). Species richness and diversity, including non-native diversity, were all greater with progressive piling ($p = < 0.001$, all variables). Two indicator plant species were found for the separate soil pile treatment including *Geranium bicknellii* Britton (Bicknell's cranesbill), while twelve were found for progressive pile areas, including *Equisetum sylvaticum*, *Betula papyrifera,* and three non-native species (Table 2.13). Both piling treatments were associated with *Calamagrostis canadensis, Rubus idaeus* and *Salix* sp. The progressive soil pile treatment was associated with forest controls by two forb species and no associates were found between separately piled soils and controls (Table 2.13).

4.3. Effect Of Woody Debris On Vegetation Development

Summary plant community characteristics were not different between low disturbance sites with mulch and cutblocks but were different between low disturbance sites with whole slash and cutblocks (Table 2.2). Indicator species analysis only identified *Populus tremuloides* as an indicator for forest controls relative to low disturbance sites with mulch or whole slash (Table 2.15). However, mulch sites rather than slash sites were different in species composition from forest controls ($p = 0.001$, Table 2.2).

Total plant cover, and that of grasses and shrubs, were greater in low disturbance sites with slash than cutblocks ($p \leq 0.05$, 0.01 and 0.01, respectively), and was the treatment most similar to cutblocks in tree cover and tree to grass shrub ratio (Table 2.4); total plant cover was also greater relative to all other treatments. Low disturbance sites with mulch had less tree cover and a lower tree to grass shrub ratio than to cutblocks ($p \leq 0.01$ and 0.001, respectively). Both mulch and slash low disturbance sites had greater shrub cover than cutblocks ($p \leq 0.05$), although shrub cover was lower than most other treatments (Table 2.4). Low disturbance sites with slash had the most indicator species relative to all treatments, cutblocks and forest controls. All treatments were associated with cutblocks by ten species, and low disturbance sites with slash were associated with cutblocks by five more species.

Compared to sites with whole slash, mulch low disturbance sites had lower forb and total plant cover, more plant litter ($p = 0.060$, 0.064 and 0.65, respectively) and less slash ($p = < 0.001$) (Table 2.14). All wood treatments were associated with *Rubus idaeus* and *Salix* sp. The mulch treatment was associated with *Cirsium arvense* L (Canada thistle) (Table 2.15) and had greater non-native diversity than cutblocks (Table 2.4). *Populus tremuloides* was an indicator for forest controls although it was not identified with the association function as associated with any treatments or controls. Therefore, aspen populations had established sufficient cover across wood treatments of low disturbance to not be significantly different from controls (Table 2.15).

When deep and shallow mulch were compared, *Populus tremuloides* was not an indicator for any treatments or controls, but *Populus balsamifera* was an indicator with deep mulch (Table 2.17). Relative to shallow mulch, deep mulch had greater moss and forb cover and more non-native diversity (p = 0.022, 0.042 and 0.012, respectively) (Table 2.16). Total tree cover and tree to grass shrub ratio were greater with shallow mulch (p = 0.022 and 0.043, respectively).

No differences in summary plant community characteristics were found between spread and windrowed treatments in progressively piled soils (Table 2.18). *Betula papyrifera* was an indicator species for the progressive soil pile windrow treatment (Table 2.20). When spread and windrow treatments from both soil pile treatments were compared to forest controls, windrow was associated with the controls by *Picea glauca* (Table 2.21). With separately piled soils, shrub cover was higher (p = 0.072) (Table 2.19) and *Populus tremuloides* regeneration was lower (where it was identified as distinctly not associates of the controls) with spread slash than with windrows (Table 2.22).

4.4. Effect Of Planted Trees On Vegetation Development

On low disturbance sites regardless of wood treatment, shrub cover was greater if non-planted (p = 0.028) (Table 2.14). *Rubus idaeus* and *Salix* sp were indicator species for the non-planted treatment (Table 2.15). On low disturbance sites with mulch, species richness was greater with planting (p = 0.018 and 0.016) (Tables 2.5 and 2.7, respectively). Tree to grass shrub ratio was greater with planting (p = 0.069 and 0.050) (Tables 2.5 and 2.7, respectively). With deep and shallow mulch, tree cover was greater if planted (p = 0.060), shrub cover was lower (p = 0.031) (Table 2.16). *Rosa acicularis* and *Lonicera villosa* (Michx) Schult (mountain fly honeysuckle) were associated with non-planting (Table 2.17), and no shrubs were associated with planting.

Low and high disturbance sites had greater tree cover (p = 0.070) and tree to grass shrub ratio (p = 0.069) with planting, with the ratio significantly greater in the planted low disturbance treatment (p = 0.039) (Table 2.5). *Populus balsamifera* was an indicator for the planted treatment; *Calamagrostis canadensis* and *Salix* sp were indicators for the non-planted treatment with high and low disturbance (Table 2.23). Species richness and diversity were greater with planting in both soil treatments (p = 0.018 and 0.010, respectively) (Table 2.5). High disturbance sites had greater native diversity if planted than both low disturbance (p = 0.010) (Table 2.5) and duff stripping treatments (p = 0.036) (Table 2.8). High disturbance and duff stripped sites had more grass in the non-planted treatment (p = 0.080) (Table 2.8).

In progressive and separate soil pile treatments, *Salix* sp was an indicator for the planted treatment and *Rubus idaeus* for the non-planted treatment. The non-planted treatment and controls were associated with *Picea glauca* (Table 2.21). Within progressively piled soils, tree cover was greater with planting (p = 0.016) (Table 2.18). The tree to grass shrub ratio was greater with planting (p = 0.037), particularly with spread slash (p = 0.038) (Table 2.18). In separately piled soils, shrub cover was greater in non-planted (p = 0.019) (Table 2.19). *Alnus crispa* and *Rubus idaeus* were indicators for the non-planted windrow treatment in separately piled soils (Table 2.22), and species richness was lower in the non-planted treatment (p = 0.073) (Table 2.19). Vegetation responded differently to planting between soil pile treatments resulting in greater tree cover and tree to grass shrub with planting of progressively piled soils (p = 0.007 and 0.036, respectively) compared to planting in separately piled soils (Table 2.12).

5. DISCUSSION

All sites have one common disturbance characteristic, vegetation was removed. Therefore, cutblocks provided a good reference to assess physical characteristics of vegetation recovery without soil disturbance, and were the closest proxy to natural regeneration. A larger sample size of cutblocks to represent a greater proportion of the study area is desirable, but cutblocks available and harvested in the appropriate time frame were limited. Since cutblocks were located in the general study area, they were considered reasonable reference sites.

Cutblocks were closest in distance to iced-in mulch sites, and thus edaphic and climatic conditions. Vegetation response was thus expected to be most similar between cutblocks and mulch sites. However, cutblocks were more similar to iced-in slash sites which were in the middle of the study area, and among other sites. Therefore, site treatment had an overriding effect that eliminated at least part of the locational bias introduced by cutblocks.

Although all offsite forest controls were upland aspen white spruce stands, they differed in age and understory composition, and therefore disturbance history beyond the scope of this study. However, we are satisfied that those differences existed equitably among treatment groups, such that results are not skewed. Use of offsite forest controls was necessary as we wanted some natural reference (in addition to comparing treatments to each other) within the context of each site’s successional potential; alternately stated, the forest controls represent a possible future state for each site if the current disturbance has not drastically altered natural successional mechanisms. A newly disturbed site is not expected to be similar to a 50 to 100 year old forest. However, we hypothesized, and found, that a number of the same species would be present if not in the same proportions. Most sites are located within mature mid-successional forests. There are only six stands that could be classified as late successional, with closed canopies, high moss cover and low diversity, but their occurrences are not concentrated or in association with any particular treatment.

An increase in plant species richness is common in post disturbance boreal forests (Pykälä 2004). Many boreal species are shade intolerant and only emerge in early successional phases of stand development (Hart and Chen 2006). These species often rely on seed banks or wind dispersal for regeneration during suitable conditions. Species richness and diversity in the current study are likely an expression of historic seed and propagule banks exposed, eliminated or increased by disturbance, and responses to changes in local resource availability.

Disturbance intensity ultimately dictates whether a disturbed site will return to forest, or if the local ecosystem will be pushed into an alternate stable state. Species available and able to re-establish immediately post-disturbance will affect what follows and how the regenerating area will respond to further disturbance (Bergeron et al 2014). Initial post-disturbance propagule availability is therefore a key predictor in stand development, which is determined by fire history and plant reproductive strategies (Kneeshaw et al 2011, Ngyuen-Xuan et al 2000).

Jaccard similarity index results suggest root salvage and duff stripping treatments were most similar to forest controls and therefore most recovered. This may seem unlikely considering their divergent community responses, with root salvage having quite high species richness and shrub cover, and duff stripping relatively low diversity and high grass cover. However, it has been a common misconception that boreal succession proceeds linearly, from highly diverse young deciduous forest to conifer stands of low diversity; disturbance in the boreal is an on-going process (Johnson and Miyanishi 2007). The first 20 years after natural disturbance (fire) in the boreal are characterized by dense vascular plant cover which gradually decreases with canopy closure, but can fluctuate as stands mature (Hart and Chen 2006). Mid to late-successional upland boreal aspen stands and aspen-conifer stands tend to maintain higher diversity over time than conifer stands with diversity peaking by age 40 after fire disturbance, slowly declining over the following 200 years (Hart and Chen 2006). Therefore, similarity of species composition must be carefully considered along with similarity of physical recovery.

Similarity of plant species composition between sites and forest controls was an important factor in assessing the extent of recovery, and potential of a site to return to pre-disturbance conditions. Equally important was evidence of canopy development, which if insufficient may indicate loss of forest to shrub or grass meadow. This was assessed with the tree to grass shrub ratio and is related to other plant community characteristics. Loss of aspen to meadow in boreal ecosites results in reduced soil productivity and availability of soil nutrients (Buck and St Clair 2012). Most early successional boreal species have high nutrient requirements (Pitt et al 2010, Hart and Chen 2006). Reduction of nutrient availability reduces number of species capable of regenerating and encourages more competitive species.

Low disturbance with whole slash resulted in the least difference from forest controls in community composition. With almost 30 % tree cover, a value almost 50 % of the understory (grass and shrub cover), this treatment was similar to cutblocks, and had greater tree cover than high disturbance treatments. Low disturbance sites with slash had greatest likelihood of returning to forest, and sooner than all other treatments. In contrast, canopy recovery was significantly lower on high disturbance sites than that on low disturbance sites. Bachmann et al (2015) found that *Populus tremuloides* regeneration and growth were more robust where low disturbance rather than excavation methods were used for site construction.

Compared to low disturbance methods, high disturbance resulted in a distinct change of ecotype. In an all-group comparison, controls, cutblocks and iced-in sites with slash had similar key understory components of upland aspen forests in this study. Species were retained from the original forest on site, likely through a combination of retention of intact roots, seeds and propagules. All treatment groups, including cutblocks, were associated with *Rubus idaeus* and *Calamagrostis canadensis*, two species known to be competitive early seral colonizers of disturbed ground which respond quickly to resource abundance (Hart and Chen 2006).

All treatment groups, including cutblocks were associated with *Equisetum arvense* and *Equisetum sylvaticum*, which are key components of the f.1 ecotype described by Beckingham and Archibald (1996). They defined this ecotype as a successional precursor to upland aspen-cranberry sites (d.1 ecotype), which can arise when post-disturbance conditions result in increased soil water content. Removal of trees and other developed vegetation are likely to increase water content due to short term reduction in transpiration (NRCWSTB 2008). However, when low and high disturbance methods were compared to forest controls, *Calamagrostis canadensis, Equisetum arvense* and *Equisetum sylvaticum* were associated with anything but low disturbance, and usually high disturbance, indicating a progressively greater shift with high disturbance away from controls a decade or so after disturbance.

Both root salvage and duff stripping were potential ways to reduce disturbance and conserve aspen roots for better regeneration. Both resulted in greater similarity to forest controls than high disturbance methods, although treatment effects remained unique. Similar to low disturbance, root salvage and duff stripping were associated with controls by *Populus tremuloides*, which shows that these treatments fulfilled the goal of conserving aspen roots relative to more intensive two-pass stripping; however, these practices did not increase tree cover after 10 years. Root salvage may be preferable as it was associated with controls by *Picea glauca* and *Populus balsamifera* was an indicator species. These findings suggest conditions may be more favourable for mixedwood establishment on root salvage treated sites.

When compared to root salvage, high disturbance practices maintained indicators of the f.1 ecotype (Beckingham and Archibald 1996), implying that root salvage either did not result in the same degree of plant community change, or recovered from disturbance more quickly. Duff stripping resulted in a more extreme change in plant community structure, with greater grass cover and lower tree cover relative to grass and shrubs in all other treatments.

Working in boreal forest soils, Qi and Scarratt (1998) found most tree and dicot seeds were located in the lower layer of organic (LFH) material. Vegetation that colonizes after natural disturbances in the boreal are predominantly from propagules embedded in the humic layer (or lower duff layer) of LFH (Hart and Chen 2006). These would be removed with duff stripping. Tree and shrub seeds are generally more prone to desiccation than other vegetation groups (Gold and Hay 2014), and may even be more susceptible when stored in relatively porous duff material at low atmosphere and freezing temperatures, and not protected by a dense soil matrix. In a greenhouse, seedling establishment of germinated seeds in disturbed or loosened organic material was lessened due to low water retention (Qi and Scarratt 1998).

Qi and Scarratt (1998) found seed composition of the upper mineral layer of boreal soil was 59 % grasses and sedges. Grass and sedge seeds may have greater longevity than other vegetation groups, such that they survive long enough to become part of the soil matrix; when soils are disturbed, grass and sedge seeds may be brought to the surface, changing the proportion of vegetation groups at initiation of secondary succession. Thus, grasses and sedges may be increasingly favoured with type and extent of soil disturbance. After establishment on clear cut sites, their contribution to local seed rain increased from 1 to 14 % (Qi and Scarratt 1998), and would create a legacy effect that lasts for some time after disturbance. This may explain greater cover of grass and low diversity with duff stripping. Grass and sedge seeds were likely exposed during duff removal. Once replaced, loose duff material could permit greater transmittance of light and warmth to mineral soil, triggering grass and sedge germination, while seeds from other vegetation groups that survived storage and germinated in duff material may have perished with dehydration. Conversely, root salvage resulted in greater species diversity, suggesting a greater variety of seeds and propagules were better protected through excavation, storage and replacement. Of all excavation treatments, root salvage may have resulted in the least change in proportions of species and vegetation groups available for revegetation.

Separate soil piling had a negative effect on species richness and diversity, resulting in low structural diversity in the understory and reduced canopy cover relative to natural revegetation compared to progressively piled soils. Similar to duff stripping, seeds and propagules were potentially at greater risk of desiccation in separate than progressive soil piles. Sites and spoil piles have a typical life span of a few winter months. Piled soils are no longer thermally protected by layers of snow, and organic material is then exposed to atmospheric pressure and lower temperatures, thereby placing vegetation propagules at risk of desiccation.

Weber (2011) found that rhizomes exposed to the atmosphere were prone to water loss and desiccation, but tolerance to drying conditions varies among species. MacKenzie (2013) found stockpiling reduced seed viability of native plant species if their seed coat was not hard, or was permeable to water, and thus susceptible to surrounding soil or atmospheric conditions. These effects would be greater in separate piles, where a larger surface area of soil was exposed relative to volume. MacKenzie (2013) found two out of 25 native boreal species had seeds that resisted the negative effects of stockpiling; one was *Geranium bicknellii*, which was one of two indicators in of the separate soil pile treatment of our experiment.

Low disturbance sites treated with whole slash resulted in physical characteristics of well site regeneration more similar to cutblocks than other treatments. It is generally well known that large woody materials left after site clearing during initial disturbance can improve reclamation outcomes (Mackenzie 2013, Naeth et al 2012, Vinge and Pyper 2012). Results in this research indicate mulch appeared to alter plant communities by deterring native forb establishment. Mulched sites were likely less productive, as they had lower total cover than low disturbance whole slash sites, and higher litter cover. Phenolic compounds in mulch leachate have potential to inhibit regrowth of many species in aspen environments (Conlin 2001). Chipping residues can alter soil hydrologic function, reduce soil productivity and nutrient availability (Kabzems et al 2011). Mulch application can result in reduced total plant diversity and cover by preventing germination of some species, and physically preventing others from emerging beneath the mulch (Miller and Seastedt 2009).

Mulch spread at depths greater than 4 cm can impede aspen plant community regrowth. Mulch imposes a physical barrier and slows regeneration by insulating soil, maintaining cool temperatures further into the growing season (Vinge and Pyper 2012, Landhäusser et al 2007). This could prevent germination of many species, and confer an advantage to those with intact root systems (shrubs). In the current study, available space that would otherwise have been taken up by native forbs on sites with mulch may have been most prone to invasion.

On high disturbance sites, windrowed slash may increase the area of suitable germination space (exposed soil) for wind dispersed tree seeds, or provide better protection of seedlings than spread slash. Woody debris can shelter seedlings of woody plants from temperature and moisture extremes (Brown and Naeth 2014). This may be more pronounced with high densities of woody debris. Where soils were piled separately with greater risk of propagule loss than progressively piled soils, windrowing improved aspen regeneration. This may be due to warming of bare soil areas between windrows, stimulating regrowth. Aspen sucker initiation is dependent upon sufficient temperature and light reaching the soil surface (Burns and Honkala 1990).

Planting trees generated multiple benefits across treatments. As expected, one direct result was greater tree cover (except where soils were piled separately). With duff stripping, grass cover was higher without planting. In almost all soil disturbance treatments, indicator species for non-planting included either *Rubus idaeus* or *Calamagrostis canadensis*. This suggests tree planting may have deterred growth of these species, or more likely, as observed by De Grandpré et al (1993) shaded them over time. *Rubus idaeus* and *Calamagrostis canadensis* can emerge after 100 years dormancy and quickly recolonize in response to disturbance (Hart and Chen 2006). This is an important consideration as these species can impede and even prevent forest establishment, thereby inhibiting recovery of boreal forest after oil sands exploration activities.

Calamagrostis canadensis has an extensive rhizomatous root system that can fragment with disturbance and lead to vigorous re-sprouting (Lieffers et al 1993). The grass can quickly take over newly disturbed sites, and significantly impact survival and growth of juvenile trees through multiple competitive means (change in light, nutrients, water and temperature). Thus, disturbing soil not only changes its composition and structure, but changes the proportion of plant species available in the propagule pool, and therefore alters successional development.

Rubus idaeus is a highly competitive species and can greatly increase post disturbance. It suppresses conifer growth including that of *Picea glauca* (Tirmenstein 1990), and can suppress some hardwood species, deterring canopy regeneration for up to 23 years (Lin et al 2014). Up to 240 seeds per m^2 were found in central Alberta upland coniferous forest; seeds retain an average viability of > 90 % for over 100 years, and reach optimal germination in 50 to 100 years, positioning the species to exploit disturbed areas. Vegetative reproduction occurs by layering and rooting from stem nodes and pieces, with root suckering especially vigorous after plant damage (Tirmenstein 1990).

Planting trees reduced impacts of oil sand exploration where propagule loss or increase in competitive species resulted in lower species richness, diversity and/or forb cover. Species richness and/or diversity was greater with mulch and high disturbance, including sites where soils were piled separately, and on duff stripping sites with planting. It is well recognized that implementing measures to assist reforestation may not only promote ability to return to a forested ecosite, but promote diversity and ecosystem function over the long term (Kuuluvainen 2002). Trees are the primary ecosystem engineers of the boreal forest, providing structural diversity and controlling microclimate conditions that in turn, influence all other plant species in their vicinity. With a greater amount of regeneration niches available, more species may re-establish more quickly, and whose interactions contribute to the overall productivity of the forest.

6. CONCLUSIONS

Disturbance intensity of oil sand exploration methods and their combinations can be characterized and categorized by degree of similarity in species composition to forest controls and similarity of vegetative regrowth to cutblocks, including development of the tree canopy relative to grass and shrub understory. These parameters are dependent upon degree of alteration to site conditions and the propagule pool from each disturbance.

Low disturbance with whole slash resulted in a relatively high tree cover and greatest likelihood of prompt return to boreal forest communities. Intact aspen roots and the greater proportional availability of propagules for regrowth through minimal soil disturbance (without removal and handling) are key factors in site recovery. Shrub growth on low disturbance sites was likely stimulated by vegetation damage and removal, but did not proportionally increase relative to other vegetation groups via root fragmentation and propagule spread. With mulch, low disturbance sites showed benefit of leaving aspen roots intact with greater tree cover and a higher tree to grass shrub ratio than high disturbance sites, although forb suppression occurred, altering the plant community and providing more space for non-native species.

Duff stripping resulted in greatest alteration of propagule representation within vegetation groups. Although intact aspen roots did result in better aspen cover than conventional stripping, other tree seedlings were likely suppressed by a high grass cover such that tree cover was not greater than that achieved by high disturbance methods.

With disturbance of mineral soil, fragmentation of *Rubus idaeus* and *Calamagrostis canadensis* roots may have occurred, resulting in an increase of propagules for regeneration. Tree and dicotyledon seeds normally found at soil surface mix into the soil matrix and buried seeds emerge. A distinct proportional change in propagule numbers of individual species, and propagules representing vegetation groups, likely occurred with conventional stripping, and alteration due to desiccation in separate soil piles. Root salvage was likely more similar to controls due to retention of large soil aggregates, and intact roots and seeds within.

Although it seems uncertain whether any treatment involving high soil disturbance can consistently become fully reforested in the absence of intervention or further disturbance, root salvage seems to be a preferable treatment. Similar to duff stripping, root salvage did not increase tree cover relative to conventional stripping, but retained greater species richness and structural diversity. Root salvage either did not result in the same degree of plant community change, or recovered from disturbance more quickly.

Windrowing contributed to improved canopy cover on high disturbance sites, providing suitable habitat for *Picea glauca*, and in the separate soil pile treatment, potentially mitigating effects of desiccation of propagules with greater aspen cover. Forest recovery was aided by planting. Where disturbance intensity altered plant community assemblages to favour competitive grasses and/or shrubs, planting trees reduced their cover, and increased species richness and/or diversity in high and low soil disturbance treatments.

Increased disturbance intensity, including soil removal, handling and associated debris treatment, reduced the likelihood of rapid and efficient reforestation after oil sands exploration disturbance. For upland boreal well sites to more consistently return to forest communities, low disturbance methods should be used, preferably with an iced-in well pad (not including mulch), leaving whole slash for distribution upon reclamation. If mulching is necessary, site managers should ensure mulch remains on site in as thin a layer as possible, and consider leaving ground patches free of mulch for propagules that require direct sun and warm conditions to regenerate.

If site levelling via soil excavation is unavoidable, selecting sites that already have observable populations of *Calamagrostis canadensis* and/or *Rubus idaeus* increases the risk of herbaceous regrowth resulting in grass or shrub meadow post reclamation. Methods should be used to preserve natural presence and proportions of plant species in the seed/propagule bank. Where possible, duff and upper mineral layers should be protected to prevent potential losses of seeds and propagules to desiccation. Although separate soil piling may reduce soil layer mixing, any benefit thereof is likely negligible due to the damage to the regeneration pool, and should thus be avoided. Separate soil piling requires a larger area than single progressive piles and therefore necessitates a larger lease size, leading to more disturbance than necessary. Overall, root salvage may be preferable, as it appears to more consistently result in less change to the local habitat, or faster recovery from disturbance, relative to other high disturbance methods.

Tree planting provided a range of benefits that contributed to faster forest recovery and increased structural and species diversity. Benefits of planting were apparent on both high and low disturbance sites, and should be a standard practice after oil sands exploration disturbance.

8. LITERATURE CITED

Bachmann, S, VJ Lieffers and SM Ländhausser. 2015. Forest floor protection during drilling pad construction promotes resprouting of aspen. Ecological Engineering 75:9-15.

Beckingham, JD and JH Archibald, 1996. Field guide to ecosites of northern Alberta. Natural Resources Canada and Canadian Forest Service, Northwest Region, Northern Forestry Centre. Edmonton Alberta. Special Report 5.

Bergeron, Y, HYH Chen, NC Kenkel, AL Leduc and SE Macdonald. 2014. Boreal mixedwood dynamics: ecological processes underlying multiple pathways. The Forestry Chronicle 90:202-213.

Bonan, GB and HH Shugart. 1989. Environmental factors and ecological processes in boreal forests. Annual Review of Ecology and Systematics 20:1-28.

Brown, RL and MA Naeth. 2014. Woody debris amendment enhances reclamation after oil sands mining in Alberta, Canada. Restoration Ecology 22:40-48.

Buck, JR and SB St Clair. 2012. Aspen increase soil moisture, nutrients, organic matter and respiration in Rocky Mountain forest communities. PLoS One 7: article number e52369.

Burns, RM and BH Honkala. 1990. Silvics of North America, volume 2, Hardwoods. Agricultural handbook Number 654. United States Department of Agriculture and Forestry Service. Washington DC. 877 pp.

Conlin, TSS. 2001. In-woods chipping: possible evidence for allelochemical interaction of leachate generated from trembling aspen (*Populus tremuloides* Michx) bark and wood waste. Forestry Chronicle 77:345-349.

De Cáceres, M. 2013. How to use the indicspecies package (ver 1.7.1). On line at https://cran.r-project.org/web/packages/indicspecies/vignettes/indicspeciesTutorial.pdf. Accessed 5 August 2016.

De Cáceres, M and F Jansen. 2015. Package 'indicspecies'; relationship between species and groups of sites. On line at https://cran.r-project.org/web/packages/indicspecies/indic species.pdf. Accessed 5 August 2016.

De Cáceres, M, P Legendre and M Moretti. 2010. Improving indicator species analysis by combining groups of sites. Oikos 119:1674-1684.

De Grandpré, L, D Gagnon and Y Bergeron. 1993. Changes in the understory of Canadian southern boreal forest after fire. Journal of Vegetation Science 4:803-810.

Dufrêne, M and P Legendre. 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecological Monographs 67:345-366.

Global Forest Watch Canada. 2005. 2005 natural regions and Subregions of Alberta [map]. Scale not given. In: Maps – the last great intact forest landscapes of Canada: Atlas of Alberta: Part 1. On line at http://global forestwatch.ca/publications/20090402A_MapsI. Accessed 15 December 2016.

Gold, K and F Hay. 2014. Identifying desiccation-sensitive seeds. Millennium Seed Bank Partnership, Technical Information Sheet 10. Royal Botanic Gardens, Kew Victoria Australia. On line at http://www.kew.org/sites/default/files/10-Desiccation%20tolerance% 20web_0.pdf. Accessed 29 October 2016.

Hart, SA and HYH Chen. 2006. Understory vegetation dynamics of North American boreal forests. Critical Reviews in Plant Sciences 25:381-397.

Hassan, R, R Scholes and N Ash (eds). 2005. Ecosystems and human wellbeing: current state and trends. Vol. 1. Millennium ecosystem assessment series. Island Press. London, United Kingdom. 948 pp.

Johnson, D, L Kershaw, A MacKinnon and J Pojar. 2009. Plants of the western boreal forest and aspen parkland. Lone Pine Publishing and the Canadian Forest Service. Edmonton Alberta. 392 pp.

Johnson, EA and K Miyanishi. 2007. Disturbance and succession. In: Plant disturbance ecology: the process and the response. Academic Press. Burlington Massachusetts. Pp 1-14.

Kabzems, R, S Dube, M Curran, B Chapman, S Berch, G Hope, M Kranabetter and C Bulmer. 2010. Maintaining soil productivity in forest biomass chipping operations best management practices for soil conservation. British Columbia Ministry of Forests and Range, Forest Science Program. Victoria British Columbia. Extension Note 98. On line at www.for.gov.bc.ca/hfd/pubs /Docs/En/En98.htm. Accessed November 2016.

Kneeshaw, D, Y Bergeron and T Kuuluvainen. 2011. Forest ecosystem structure and disturbance dynamics across the circumboreal forest. Pages 261-278 In: A Millington, M Blumler and U Schickhoff (eds). The SAGE handbook of biogeography. SAGE Publications. London United Kingdom.

Kreutzweiser, D, F Beall, K Webster, D Thompson and I Creed. 2013. Impacts and prognosis of natural resource development on aquatic biodiversity in Canada's boreal zone. Environmental Review 21:227-259.

Kuuluvainen, T. 2002. Natural variability of forests as a reference for restoring and managing biological diversity in boreal Fennoscandia. Silva Fennica 36:97-125.

Landhäusser, SM, VJ Lieffers and P Chow. 2007. Impact of chipping residues and its leachate on the initiation and growth of aspen root suckers. Canadian Journal of Soil Science 87:361-367.

Legendre, P and L Legendre. 1998. Numerical ecology. Second edition. Elsevier Science. Amsterdam Netherlands. 853 pp plus appendices.

Lieffers, VJ, SE Macdonald and EH Hogg. 1993. Ecology of and control strategies for Calamagrostis canadensis in boreal forest sites. Canadian Journal of Forest Research 23:2070-2077.

Lin, N, N Bartsch and T Vor. 2014. Long-term effects of gap creation and liming on understory vegetation with a focus on tree regeneration in a European beech (Fagus sylvatica L) forest. Annals of Forest Research 57:233-246.

Mackenzie, DD 2013. Oil sands mine reclamation using boreal forest surface soil (LFH) in northern Alberta. PhD dissertation. Department of Renewable Resources, University of Alberta. Edmonton Alberta. 240 pp.

Miller, EM and TR Seastedt. 2009. Impacts of woodchip amendments and soil nutrient availability on understory vegetation establishment following thinning of a ponderosa pine forest. Forest Ecology and Management 258:263-272.

Moss, EH. 1983. Flora of Alberta. Second edition. University of Toronto Press. Toronto Ontario. 687 pp.

Naeth, MA, R Brown and S Wilkinson. 2012. Use of woody debris as an amendment for reclamation after oil sands mining. Prepared for Canadian Oil Sands Network for Research and Development (CONRAD). Edmonton Alberta. 34pp.

National Research Council (US) Water Science and Technology Board (NRCWSTB). 2008. Forest disturbance and management effects on Hydrology. Pages 45-73. In: Hydrologic effects of a changing forest landscape. National Academies Press. Washington District of Columbia.

Natural Regions Committee 2006. Natural regions and subregions of Alberta. Compiled by DJ Downing and WW Pettapiece. Government of Alberta. Pub. No. T/852. Edmonton Alberta.

Nguyen-Xuan, T, Y Bergeron, D Simard, JW Fyles and D Pare. 2000. The importance of forest floor disturbance in the early regeneration patterns of the boreal forest of western and central Quebec: a wildfire versus logging comparison. Canadian Journal of Forest Research 30:1353-1364.

Nishi, JS, S Berryman, JB Stelfox, A Garibaldi and J Straker. 2013. Fort McKay cumulative effects project: technical report of scenario modeling analyses with ALCES®. ALCES Landscape and Land Use. Calgary Alberta. Integral Ecology Group. Victoria British Columbia. Prepared for the Fort McKay Sustainability Department. Fort McMurray Alberta. 126 pp plus appendices.

Oksanen, J, FG Blanchet, R Kindt, P Legendre, PR Minchin, RB O'Hara, GL Simpson, P Solymos, MHH Stevens and H Wagner. 2015. Package ‘vegan’; the community ecology package. On line at http://cran.r-project.org, https://github.com/vegandevs/vegan. Accessed 25 March 2015.

Paradis, E, J Claude and K Strimmer. 2004. Package ‘ape’: analyses of phylogenetics and evolution in R language. Bioinformatics 20:289-290.

Pitt, DG, PG Comeau, WC Parker, D MacIsaac, S McPherson, MK Hoepting, A Stinson and M Mihajlovich. 2010. Early vegetation control for the regeneration of a single-cohort, intimate mixture of white spruce and trembling aspen on upland boreal sites. Canadian Journal of Forest Research 40:594-564.

Poos, MS and DA Jackson. 2011. Addressing the removal of rare species in multivariate bioassessments: the impact of methodological choices. Ecological Indicators 18:82-90.

Pykälä, J. 2004. Immediate increase in plant species richness after clear-cutting of boreal herb-rich forests. Applied Vegetation Science 7:29-34.

Qi, MQ and JB Scarratt. 1998. Effect of harvesting method on seed bank dynamics in a boreal mixedwood forest in northwestern Ontario. Canadian Journal of Botany 76:872-883.

Quinn, G and M Keough. 2011. Experimental design and data analysis for biologists. Cambridge University Press. Cambridge United Kingdom. 537 pp.

R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna Austria. URL https://www.R-project.org/.

Ripley, B, B Venables, DM Bates, K Hornik, A Gebhardt and D Firth. 2016. Package ‘MASS’; support functions and datasets for venables and Ripley’s MASS. On line at https://cran.rproject. org/web/packages/MASS/MASS.pdf. Accessed 8 August 2016.

Roberts, DW. 2016. Package ‘labdsv’; Ordination and multivariate analysis for ecology. On line at http://ecology.msu.montana.edu/labdsv/R. Accessed 4 August 2016.

Rowe, JS. 1972. Forest regions of Canada. Fisheries and Environment Canada, Canadian Forest Service. Publication No.1300. Ottawa Ontario.

Schneider, R and S Dyer. 2006. Death by a thousand cuts; impacts of in situ oil sands development on Alberta’s boreal forest. The Pembina Institute and Canadian Parks and Wilderness Society. Edmonton Alberta. ISBN 0-921719-83-3, 1st ed. 1:0-06-07-18.

Tannas, K. 2001. Common plants of the western rangelands. Volume 1, Grasses and grass-like species. Olds College and Alberta Agriculture, Food and Rural Development. Lethbridge Alberta. 335 pp.

Tirmenstein, D. 1990. *Rubus idaeus*. In: Fire Effects Information System. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). On line at http://www.fs.fed.us/database/feis/. Accessed 17 August 2016.

Venier, LA, ID Thompson, R Fleming, J Malcolm, I Aubin, JA Trofymow, D Langor, R Sturrock, C Patry, RO Outerbridge, SB Holmes, S Haeussler, L De Grandpré, HYH Chen, E Bayne, A Arsenault and JP Brandt. 2014. Effects of natural resource development on the terrestrial biodiversity of Canadian boreal forests. Environmental Review 22:457-490.

Vinge, T and M Pyper. 2012. Managing woody materials on industrial Sites. Alberta School of Forest Science and Management, University of Alberta. Edmonton Alberta.

Weber, E. 2011. Strong regeneration ability from rhizome fragments in two invasive clonal plants (Solidago canadensis and S. gigantea). Biological Invasions 13:2947-2955.

Table 2.1. Summary of well sites and treatments in the study.

Year Company	Site Location	Soil Treatment	Soil Excavation		Soil Storage Method		Woody Material Management			Trees	
			No	Yes	Progressive Pile	Separate Piles	Mulch Spread	Whole Slash Spread	Whole Slash Wind-rowed	Non-Planted	Planted
2004 – 1	16-31-85-06 06-29-85-06N 06-29-85-06S	Iced-in	√		n/a		√ Shallow & Deep			√	√
2004 – 1	02-19-85-06 05-29-85-06 01-05-86-06 16-05-86-06 11-12-86-07	Iced-in	√		n/a		√			√	√
2005 – 1	11-19-84-06 06-30-84-06	Iced-in	√		n/a			√	√	√	√
2006 – 1	13-25-84-07 16-26-84-07 02-26-84-07	Iced-in	√		n/a		√			√	√
2004 – 2	13-07-82-06 11-17-82-06 14-29-82-06 05-32-82-06 12-23-82-07	Stripped 2 passes		√	√			√		√	√
2005 – 2	03-04-82-06 08-01-83-06	Stripped 2 passes		√	√			√	√	√	√
2006 – 2	02-17-82-06			√	√			√	√	√	√
2006 – 1	02-33-84-07 08-28-84-07 10-26-84-07	Stripped 2 passes		√		√		√	√	√	√
2006 – 2	06-13-82-06 15-11-82-06 12-33-81-06	Duff stripped		√ minimal	√			√		√	√
2006 – 1	2-35-84-07 16-28-84-07 03-33-84-07 14-28-84-07 11-28-84-07 13-22-84-07	Root salvage		√		√		√		√	

Table 2.2. PerMANOVA results evaluating plant species compositional differences among treatment groups including cutblocks and associated non-treated controls and summary plant community characteristics between treatment groups and cutblocks on northern Alberta boreal well sites.

	Controls						Cutblock					
PerMANOVA	Df	Sum of Squares	Mean Squares	F Model	R2	Pr > F	Df	Sum of Squares	Mean Squares	F Model	R2	Pr > F
Cutblock	1	0.2927	0.2927	1.5	0.18	0.135	-	-	-	-	-	-
Site (random)	3	0.7527	0.2509	1.3	0.46	0.198	-	-	-	-	-	-
Residuals	3	0.5787	0.1929		0.36		-	-	-		-	
Total	7	1.6241			1.00		-	-			-	
Low slash	1	0.3675	0.3675	6.9	0.71	0.167	1	4786.1	4786.1	7.5	0.65	0.067
Site (random)	1	0.1016	0.1016	1.9	0.19	0.500	-	-	-	-	-	-
Residuals	1	0.0531	0.0531		0.10		4	2563.3	640.8		0.35	
Total	3	0.5222			1.00		5	7349.4			1.00	
Low mulch	1	0.9892	0.9892	8.0	0.28	0.001	1	5307.0	5307.5	2.0	0.17	0.137
Site (random)	7	1.7336	0.2477	2.0	0.48	0.006	-	-	-	-	-	-
Residuals	7	0.8653	0.1236		0.24		10	26529.0	2652.9	-	0.83	
Total	15	3.5882			1.00		11	31836.0			1.00	
Root salvage	1	1.0654	1.0654	16.5	0.67	0.005	1	6878.3	6878.3	10.6	0.60	0.009
Site (random)	4	0.2638	0.0660	1.0	0.17	0.411	-	-	-	-	-	-
Residuals	4	0.2581	0.0645		0.16		7	4562.9	651.8		0.40	
Total	9	1.5873			1.00		8	11441.1			1.00	
High progressive	1	1.8009	1.8009	25.1	0.55	0.001	1	6423.4	6423.4	7.0	0.41	0.003
Site (random)	7	0.9523	0.1360	1.9	0.29	0.061	-	-	-	-	-	-
Residuals	7	0.5015	0.0716		0.16		10	9187.1	918.7	-	0.59	
Total	15	3.2547			1.00		11	15610.5			1.00	
High separate	1	0.7103	0.7103	10.5	0.68	0.017	1	7831.7	7831.7	11.3	0.69	0.023
Site (random)	2	0.2065	0.1033	1.5	0.20	0.367	-	-	-	-	-	-
Residuals	2	0.1354	0.0677		0.12		5	3459.3	681.9		0.31	
Total	5	1.0522			1.00		6	11291.0			1.00	
Duff stripping	1	0.7422	0.7422	4.9	0.51	0.017	1	4994.3	4994.3	4.5	0.47	0.033
Site (random)	2	0.4177	0.2089	1.4	0.29	0.383	-	-	-	-	-	-
Residuals	2	0.3008	0.1504		0.20		5	5541.4	1108.3		0.53	
Total	5	1.4607			1.00		6	10535.6			1.00	

Table 2.3. Significant (p ≤ 0.02) indicator and associated plant species for low soil disturbance with slash (LS, n=2) and mulch (LM, n=8), root salvage (RS, n=5), high soil disturbance with progressive piling (HP, n=8) and separate piling (HS, n=3) and duff stripping (DS, n=3) treatments and not-treated cutblocks (CUT, n=4) and controls (CON, n=29) at northern Alberta boreal well sites. Associate species are shown as positively (+) or negatively (-) associated to groups.

	Indicator Score									Association									
Species	CON	CUT	LS	LM	RS	HP	HS	DS	p-value	CON	CUT	LS	LM	RS	HP	HS	DS	Score	p-value
Lycopodium annotinum	0.669								0.006										
Viburnum edule	0.474								0.003	+	+	+	-	-	-	-	-	0.916	0.005
Pyrola asarifolia	0.418								0.016										
Populus tremuloides	0.403								0.001										
Linnea borealis		0.482							0.002	+	+	+	-	-	-	-	-	0.918	0.005
Cornus canadensis		0.328							0.005										
Stellaria media			0.857						0.002	-	-	+	-	-	-	-	-	0.857	0.015
Lycopodium obscurum			0.709						0.004	-	-	+	-	-	-	-	-	0.709	0.005
Pedicularis labradorica			0.640						0.009	-	-	+	-	-	-	-	-	0.640	0.015
Vaccinium caespitosum			0.635						0.008	-	-	+	-	-	-	-	-	0.635	0.015
Geum rivale			0.610						0.005	-	-	+	-	-	-	-	-	0.610	0.010
Trifolium repens			0.561						0.010										
Botrychium virginianum					0.598				0.008	-	-	-	-	+	-	-	-	0.590	0.015
Matteuccia struthiopteris							0.684		0.005	-	-	-	-	+	-	+	-	0.884	0.005
Impatiens noli-tangere							0.644		0.012	-	-	-	-	-	-	+	-	0.643	0.015
Alnus crispa							0.437		0.006	-	-	-	-	+	+	+	-	0.824	0.005
Tanacetum vulgare								0.667	0.007	-	-	-	-	-	-	-	+	0.666	0.010
Agropyron trachycaulum										-	-	-	-	-	+	-	+	0.706	0.005
Lycopodium annotinum										+	-	+	-	-	-	-	-	0.760	0.005
Aquilegia brevifolia										-	-	+	-	+	-	+	-	0.564	0.020
Bromus ciliatus										-	-	+	-	-	+	+	+	0.704	0.015
Viola canadensis										-	-	-	-	+	+	+	+	0.677	0.015
Lathyrus venosus										-	+	+	-	+	-	-	-	0.643	0.005
Potentilla norvegica										-	-	+	+	-	-	+	+	0.746	0.010
Agrostis stolonifera										-	-	-	+	+	+	+	+	0.663	0.005
Achillea sibirica										-	-	+	+	-	+	+	+	0.634	0.015
Aralia nudicaulis										+	+	+	-	-	-	-	-	0.810	0.010
Mitella nuda										+	+	+	-	+	-	+	-	0.920	0.015
Salix sp.										-	-	+	+	+	+	+	+	0.968	0.005
Populus balsamifera										-	-	+	+	+	+	+	+	0.880	0.005
Galium triflorum										-	-	+	+	+	+	+	+	0.867	0.005
Poa pratensis										-	-	+	+	+	+	+	+	0.776	0.005
Carex sp.										-	+	+	+	+	+	+	+	0.996	0.005
Rubus idaeus										-	+	+	+	+	+	+	+	0.994	0.005
Equisetum sylvaticum										-	+	+	+	+	+	+	+	0.986	0.005
Betula papyrifera										-	+	+	+	+	+	+	+	0.956	0.005
Epilobium angustifolium										-	+	+	+	+	+	+	+	0.943	0.005
Vicia americana										-	+	+	+	+	+	+	+	0.927	0.005
Equisetum arvense										-	+	+	+	+	+	+	+	0.914	0.005
Calamagrostis canadensis										-	+	+	+	+	+	+	+	0.903	0.010
Taraxacum officinale										-	+	+	+	+	+	+	+	0.864	0.005
Achillea millefolium										-	+	+	+	+	+	+	+	0.796	0.010

Table 2.4. Permutational ANOVA results, means and standard errors evaluating summary plant community characteristics for cutblocks against soil treatments including low disturbance with slash or mulch treatments, duff stripping, high disturbance with progressive or separate soil piling and root salvage treatments on northern Alberta boreal well sites. ANOVA p-values indicate significance of variation between all groups. Treatment means significantly different from cutblocks are marked: ^{p} ($p \leq 0.08$), * ($p \leq 0.05$), ** ($p \leq 0.01$) and *** ($p \leq 0.001$).

Treatments (n), Means and Standard Errors	Litter (%)		Moss (%)		Slash (%)		Bare Ground (%)		Total Cover (%)		Grass Cover (%)		Forb Cover (%)	
ANOVA p-values, df=6	0.008		0.483		0.010		0.742		0.035		0.083		0.159	
Cutblock (4)	74.0		11.2		14.8		0.00		108.3		7.1		36.2	
Low slash (2)	79.9	+/-2.7	7.3	+/-1.8	12.6	+/-1.0	0.16**	+/-0.08	152.4*	+/-20.8	20.8**	+/-6.5	61.1^{p}	+/-11.7
Low mulch (8)	78.6	+/-2.2	15.4	+/-2.0	5.7*	+/-4.3	0.29	+/-0.14	129.1	+/-9.8	19.9	+/-6.0	39.8	+/-1.7
Root salvage (5)	94.4**	+/-10.1	1.4*	+/-4.2	4.1**	+/-4.6	0.07	+/-0.03	119.8	+/-4.9	11.1	+/-2.0	42.3	+/-2.6
High separate (3)	93.5*	+/-9.6	2.1^{p}	+/-4.5	4.3*	+/-5.2	0.09*	+/-0.05	130.0*	+/-10.8	16.6	+/-4.7	32.7	+/-1.7
High progressive (8)	87.2*	+/-6.2	7.2	+/-1.9	5.3**	+/-4.5	0.31^{p}	+/-0.15	123.7^{p}	+/-7.2	16.4^{p}	+/-4.4	46.1	+/-4.6
Duff stripping (3)	90.4	+/-8.1	4.5	+/-3.3	5.0	+/-4.8	0.06	+/-0.03	86.9	+/-10.6	30.6***	+/-11.6	20.4	+/-7.8

Treatments (n), Means and Standard Errors	Shrub Cover (%)		Tree Cover (%)		Tree : Grass Shrub		Species Richness		SW Native Diversity*		SW Non-Native Diversity*		Jaccard Similarity Index	
ANOVA p-values, df=6	0.008		0.001		0.003		0.095		0.204		0.412		0.686	
Cutblock (4)	20.2		44.7		1.84		10.8		1.75		0.00		0.36	
Low slash (2)	42.4*	+/-10.4	28.1	+/-7.8	0.47	+/-0.65	14.7	+/-1.8	2.01	+/-0.12	0.03	+/-0.01	0.37	+/-0.01
Low mulch (8)	47.4*	+/-12.8	21.9**	+/-10.7	0.37**	+/-0.69	13.2	+/-1.1	1.81	+/-0.03	0.05^{p}	+/-0.02	0.33	+/-0.02
Root salvage (5)	54.8**	+/-17.2	12.3**	+/-16.1	0.20***	+/-0.82	17.3*	+/-3.2	1.91	+/-0.08	0.02	+/-0.01	0.39	+/-0.01
High separate (3)	63.9***	+/-21.6	16.8*	+/-13.8	0.21*	+/-0.80	12.4	+/-0.8	1.59	+/-0.08	0.01	+/-0.003	0.35	+/-0.01
High progressive (8)	47.4**	+/-12.8	13.8**	+/-14.6	0.22***	+/-0.76	15.1^{p}	+/-2.0	1.89	+/-0.07	0.11	+/-0.05	0.33	+/-0.02
Duff stripping (3)	25.8	+/-2.8	10.0**	+/-17.2	0.17*	+/-0.83	13.3	+/-1.2	1.50	+/-0.12	0.05	+/-0.02	0.38	+/-0.01

*Shannon Weiner index

Table 2.5. PerMANOVA results evaluating plant species compositional responses and two-way ANOVA means and standard errors evaluating summary plant community characteristics for high (n=5) versus low (n=5) soil disturbance and planting treatments on northern Alberta boreal well sites. Differences among least square means are indicated by different letters.

PerMANOVA	Df	Sum of Squares	Mean Squares	F Model	R2	Pr > F
Soil treatment	1	0.281	0.281	10.3	0.13	0.001
Planting treatment	1	0.032	0.032	1.2	0.02	0.335
Site (random)	8	1.527	0.191	7.0	0.73	0.001
Soil * planting	1	0.024	0.024	0.9	0.01	0.549
Residuals	8	0.219	0.027		0.11	
Total	19	2.083			1.00	

Means and ANOVA	Litter (%)	Moss (%)	Slash (%)	Bare Ground (%)	Total Cover (%)	Grass Cover (%)	Forb Cover (%)	Shrub Cover (%)	Tree cover (%)	Tree : Grass Shrub	Species Richness	SW Native Diversity*	SW Non - Native Diversity*	Jaccard Similarity Index
Soil treatments														
p-values, 1 df	0.190	0.099	0.085	0.907	0.003	0.541	0.005	0.132	0.005	0.001	0.254	0.548	0.114	0.561
Low disturbance	73.1	18.8	7.7	0.46	128.8	19.2	42.6	47.2	19.8	0.33	12.5	1.84	0.06	0.31
High disturbance	86.7	8.2	4.8	0.35	117.7	18.9	43.3	44.9	10.7	0.19	13.4	1.81	0.07	0.30
Standard errors	+/-9.5	+/-4.8	+/-1.8	+/-0.03	+/-7.6	+/-1.6	+/-7.7	+/-4.9	+/-6.6	+/-0.15	+/-0.4	+/-0.02	+/-0.03	+/-0.01
Planting treatments														
p-values, 1 df	0.504	0.393	0.070	0.467	0.599	0.088	0.108	0.645	0.070	0.069	0.018	0.010	0.322	0.243
Planted	80.3	11.9	7.6	0.24	124.0	15.5	45.5	45.1	17.8	0.30	13.6	1.89	0.07	0.31
Non-planted	79.4	15.2	4.8	0.57	122.6	22.5	40.3	47.0	12.7	0.21	12.3	1.74	0.05	0.30
Standard errors	+/-3.4	+/-2.3	+/-1.9	+/-0.23	+/-1.0	+/-5.0	+/-3.7	+/-1.4	+/-3.7	+/-0.06	+/-0.9	+/-0.10	+/-0.02	+/-0.01
Soil * Planting														
p-values, 1df	0.089	0.236	0.592	0.467	0.021	0.385	0.172	0.194	0.052	0.039	0.331	0.346	0.753	0.437
Low Planted	76.3	14.9	8.7	0.13	133.3a	17.3	47.4	43.3	25.3a	0.42a	13.4	1.92	0.06	0.32
Low Non-planted	69.8	22.8	6.6	0.78	124.4a	21.0	37.8	51.2	14.4b	0.23b	11.6	1.74	0.05	0.29
High Planted	84.2	8.9	6.5	0.35	114.7b	13.7	43.7	46.8	10.5b	0.19b	13.8	1.85	0.08	0.31
High Non-planted	89.1	7.5	3.0	0.35	120.8b	24.0	42.8	42.9	11.0b	0.18b	13.0	1.76	0.05	0.30
Standard errors	+/-4.0	+/-3.3	+/-0.5	+/-0.52	+/-5.3	+/-2.3	+/-3.1	+/-4.2	+/-4.0	+/-0.07	+/-0.3	+/-0.03	+/-0.01	+/-0.01
Site (random)														
p-values, 8 df	<0.001	0.001	0.100	0.559	<0.001	0.017	0.001	0.014	0.020	0.008	<0.001	<0.001	0.004	0.002

*Shannon Weiner index

Table 2.6. Summary of significant (p≤0.05) indicator and associated plant species for high (HI, n=5) and low (LO, n=5) soil disturbance treatments and not-treated high disturbance and low disturbance controls (HCON, LCON, respectively, n=5) on northern Alberta boreal well sites. Indicator values represent strength of a species affinity to a site group. Association scores represent strength of a species affinity for a group of sites. Significant species associations (p≤0.05) are shown as positively (+) or negatively (-) associated to groups.

	Indicator Score				P-Value (s)		Association				Score (s)	
Species	HCON	LCON	HI	LO	HCON / HI	LCON / LO	HCON	LCON	HI	LO	HCON / HI	LCON / LO
Linnea borealis	0.967	0.893			0.008	0.010	+	+	-	-	0.967	0.893
Viburnum edule	0.992				0.014		+		-		0.992	
Populus tremuloides	0.978	0.836			0.005	0.007	+		-		0.978	
Aralia nudicaulis	0.960				0.026		+		-		0.960	
Mitella nuda	0.952	0.949			0.009	0.015	+	+	-	-	0.952	0.948
Cornus canadensis	0.931				0.012		+		-		0.931	
Maianthemum canadensis	0.893	0.763			0.012	0.021	+		-		0.893	
Pyrola asarifolia	0.819				0.025							
Lycopodium annotinum		1.000			0.013			+		-		1.000
Picea mariana								+		-		0.799
Carex sp.			0.986	0.923	0.017	0.037	-	-	+	+	0.986	0.972
Vicia americana			0.983		0.010		-		+		0.983	
Rubus idaeus			0.947	0.970	0.013	0.004	-	-	+	+	0.947	0.970
Equisetum sylvaticum			0.946		0.007							
Calamagrostis canadensis			0.916		0.017		-		+		0.916	
Salix sp.			0.915		0.009		-	-	+	+	0.915	0.895
Epilobium angustifolium			0.908	0.885	0.004	0.046		-		+		0.885
Gallium triflorum			0.871	0.791	0.015	0.045		-		+		0.790
Viola adunca			0.813		0.023							
Equisetum arvense			0.788		0.020							
Poa pratensis			0.754		0.043		-		+		0.754	
Achillea sibirica			0.800		0.044		-	-	+	+	0.799	0.799
Populus balsamifera								-		+		0.799
Equisetum sylvaticum							-		+		0.946	
Achillea millefolium							-		+		0.799	
Taraxacum officinale							-		+		0.799	
Equisetum arvense							-		+		0.788	

Table 2.7. PerMANOVA results evaluating plant species compositional responses and two-way ANOVA results, means and standard errors for evaluating plant community characteristics between low disturbance (n=5) and duff striping (n=3) soil handling treatments and tree planting, on northern Alberta boreal well sites. Differences among least square means are indicated by different letters.

PerMANOVA	Df	Sum of Squares	Mean Squares	F Model	R2	Pr > F
Soil treatment	1	0.556	0.556	11.5	0.16	0.001
Planting treatment	1	0.084	0.084	1.7	0.02	0.184
Site (random)	6	2.559	0.426	8.8	0.73	0.001
Soil * planting	1	0.041	0.041	0.8	0.01	0.477
Residuals	6	0.290	0.048		0.08	
Total	15	3.530				

Means and ANOVA	Litter (%)	Moss (%)	Slash (%)	Bare Ground (%)	Total Cover (%)	Grass Cover (%)	Forb Cover (%)	Shrub Cover (%)	Tree Cover (%)	Tree : Grass Shrub	Species Richness	SW Native Diversity*	SW Non Native Diversity*	Jaccard Similarity Index
Soil treatments														
p-values, 1 df	0.130	0.007	0.189	0.979	<0.001	0.015	0.023	<0.001	0.019	0.017	0.091	<0.001	0.053	0.240
Low disturbance	73.1	18.8	7.7	0.46	128.8	19.2	42.6	47.2	19.8	0.33	12.5	1.84	0.06	0.31
Duff stripping	90.4	4.5	5.0	0.06	86.9	30.6	20.4	25.8	10.0	0.17	13.3	1.50	0.05	0.38
Standard errors	+/-11.9	+/-9.8	+/-1.8	+/-0.27	+/-28.7	+/-4.2	+/-15.1	+/-1.9	+/-6.8	+/-0.11	+/-0.36	+/-0.04	+/-0.04	+/-0.01
Planting treatments														
p-values, 1 df	0.390	0.304	0.891	0.493	0.016	0.132	0.012	0.053	0.116	0.050	0.016	0.053	0.765	0.127
Planted	81.4	11.5	7.0	0.08	114.2	21.5	38.1	35.6	18.9	0.32	13.5	1.80	0.06	0.34
Non-planted	77.7	15.4	6.3	0.53	112.0	25.4	30.4	42.8	13.4	0.21	12.1	1.62	0.05	0.32
Standard errors	+/-1.9	+/-2.8	+/-0.2	+/-0.32	+/-1.5	+/-2.7	+/-5.5	+/-4.8	+/-3.9	+/-0.08	+/-0.81	+/-0.13	+/-0.01	+/-0.01
Soil * Planting														
p-values, 1df	0.242	0.192	0.370	0.630	0.043	0.995	0.264	0.787	0.059	0.090	0.206	0.787	0.678	0.547
Low Planted	76.3	14.9	8.7	0.13	133.3a	17.3	47.4	43.3	25.3a	0.42	13.4	1.92	0.06	0.32
Low Non-planted	69.8	22.8	6.6	0.78	124.4a	21.0	37.8	51.2	14.4b	0.23	11.6	1.74	0.05	0.29
Duff Planted	89.9	5.9	4.3	0.00	82.3b	28.5	22.8	22.8	8.3b	0.16	13.6	1.60	0.04	0.38
Duff Non-planted	91.0	3.1	5.8	0.12	91.4b	32.7	18.1	28.9	11.7b	0.17	13.0	1.41	0.05	0.37
Standard errors	+/-2.6	+/-3.6	+/-1.2	+/-0.18	+/-6.15	+/-0.2	+/-1.7	+/-0.6	+/-4.9	+/-0.07	+/-0.40	+/-0.003	+/-0.01	+/-0.004
Site (random)														
p-values, 8 df	<0.001	<0.001	0.063	0.583	<0.001	0.006	<0.001	0.001	0.054	0.028	<0.001	<0.001	0.154	<0.001

*Shannon Weiner index

Table 2.8. PerMANOVA results evaluating plant species compositional responses and two-way ANOVA results, means, and standard errors for evaluating plant community characteristics between high disturbance (n=5) and duff striping (n=3) soil handling treatments and tree planting, on northern Alberta boreal well sites.

PerMANOVA	Df	Sum of Squares	Mean Squares	F Model	R2	Pr > F
Soil treatment	1	0.496	0.496	12.2	0.18	0.001
Planting treatment	1	0.025	0.025	0.6	0.01	0.681
Site (random)	6	1.966	0.328	8.1	0.71	0.001
Soil * planting	1	0.032	0.032	0.8	0.01	0.537
Residuals	6	0.243	0.041		0.09	
Total	15	2.762			1.00	

Means and ANOVA	Litter (%)	Moss (%)	Slash (%)	Bare Ground (%)	Total Cover (%)	Grass Cover (%)	Forb Cover (%)	Shrub Cover (%)	Tree Cover (%)	Tree : Grass Shrub	Species Richness	SW Native Diversity*	SW Non-Native Diversity*	Jaccard Similarity Index
Soil treatments														
p-values, 1 df	0.239	0.312	0.402	0.353	<0.001	0.017	<0.001	0.011	0.776	0.604	0.801	0.001	0.430	0.001
High disturbance	86.7	8.2	4.8	0.4	117.7	18.9	43.3	44.9	10.7	0.19	13.4	1.81	0.07	0.30
Duff stripping	90.4	4.5	5.0	0.1	86.9	30.6	20.4	25.8	10.0	0.17	13.3	1.50	0.05	0.38
Standard errors	+/-2.9	+/-1.9	+/-0.2	+/-0.2	+/-21.1	+/-8.0	+/-15.6	+/-13.1	+/-0.5	+/-0.01	+/-0.06	+/-0.21	+/-0.01	+/-0.05
Planting treatments														
p-values, 1 df	0.233	0.700	0.133	0.291	0.004	0.080	0.352	0.979	0.682	0.717	0.309	0.036	0.401	0.556
Planted	86.4	7.8	5.7	0.22	102.6	19.3	35.9	37.8	9.6	0.17	13.8	1.76	0.07	0.33
Non-planted	89.8	5.9	4.0	0.26	109.7	27.3	33.5	37.7	11.3	0.18	13.0	1.63	0.05	0.33
Standard errors	+/-3.9	+/-5.0	+/-1.1	+/-0.03	+/-5.1	+/-5.7	+/-1.6	+/-0.1	+/-1.1	+/-0.01	+/-0.54	+/-0.09	+/-0.01	+/-0.01
Soil * Planting														
p-values, 1df	0.501	0.729	0.163	0.559	0.284	0.449	0.441	0.380	0.446	0.913	0.955	0.401	0.452	0.810
Site (random)														
p-values, 8 df	0.050	0.319	0.009	0.495	<0.001	0.118	0.054	0.045	0.003	0.005	0.001	0.001	0.002	<0.001

*Shannon Weiner index

Table 2.9. Summary of significant ($p \leq 0.05$) indicator and associated plant species for low disturbance (LO, n=5), high disturbance (HI, n=5) and duff stripping (DUFF, n=3) soil treatments and not-treated controls (CON, n=13) at applicable northern Alberta boreal well sites. Associate species are shown as positively (+) or negatively (-) associated to groups.

	Indicator Score					Association					
Species	CON	LO	HI	DUFF	p-value	CON	LO	HI	DUFF	Score	p-value
Viburnum edule	0.869				0.001	+	+	-	-	0.874	0.010
Mitella nuda	0.866				0.001						
Linnea borealis	0.856				0.001	+	+	-	-	0.884	0.025
Populus tremuloides	0.774				0.001	+	+	-	+	0.984	0.005
Lycopodium annotinum	0.769				0.006	+	-	-	-	0.769	0.010
Maianthemum canadensis	0.692				0.001	+	+	+	-	0.897	0.035
Cornus canadensis	0.606				0.001	+	+	-	+	0.941	0.015
Aralia nudicaulis	0.599				0.040						
Pyrola secunda	0.534				0.037						
Lathyrus ochroleucus		0.669			0.020						
Trifolium repens		0.600			0.014	-	+	-	-	0.601	0.015
Ribes oxycanthoides			0.769		0.015	-	-	+	-	0.769	0.025
Geum macrophyllum			0.600		0.012	-	-	+	-	0.601	0.025
Poa palustris			0.593		0.030						
Galium triflorum			0.565		0.045	-	+	+	+	0.882	0.010
Viola adunca			0.561		0.028						
Cornus stolonifera			0.587		0.039						
Populus balsamifera				0.667	0.022	-	+	+	+	0.885	0.005
Tanacetum vulgare				0.667	0.010	-	-	-	+	0.666	0.010
Viola canadensis				0.649	0.019	-	-	-	+	0.649	0.010
Agropyron trachycaulum				0.649	0.020	-	-	+	+	0.733	0.015
Agrostis scabra				0.588	0.020	-	-	+	+	0.635	0.035
Phleum pratense				0.517	0.043	-	-	-	+	0.517	0.040
Calamagrostis inexpansa						-	-	-	+	0.663	0.010
Bromus ciliatus						-	-	+	+	0.624	0.020
Epilobium glandulosum						-	-	+	+	0.578	0.040
Potentilla norvegica						-	+	-	+	0.621	0.020
Pyrola asarifolia						+	-	-	+	0.767	0.030
Achillea sibirica						-	+	+	-	0.781	0.025
Carex sp.						-	+	+	+	0.994	0.005
Rubus idaeus						-	+	+	+	0.988	0.005
Salix sp.						-	+	+	+	0.966	0.005
Equisetum sylvaticum						-	+	+	+	0.951	0.015
Equisetum arvense						-	+	+	+	0.947	0.005
Calamagrostis canadensis						-	+	+	+	0.906	0.035
Vicia americana						-	+	+	+	0.891	0.005
Taraxacum officinale						-	+	+	+	0.766	0.020
Halenia deflexa						-	+	+	+	0.615	0.035

Table 2.10. PerMANOVA results evaluating plant species compositional responses between high disturbance (n=5) and root salvage treatments (n=5). PerMANOVA, one-way ANOVA results, means and standard errors evaluating summary plant community characteristics between high disturbance and root salvage treatments on northern Alberta boreal well sites.

PerMANOVA (species)	Df	Sum of squares	Mean squares	F model	R2	Pr > F
Soil treatment	1	0.118	0.118	1.8	0.18	0.014
Residuals	8	0.529	0.066		0.82	
Total	9	0.647			1.00	
PerMANOVA (characteristics)						
Soil treatment	1	994.9	994.89	1.2	0.13	0.321
Residuals	8	6490.1	811.26		0.87	
Total	9	7485.0			1.00	

Means and ANOVA	Litter (%)	Moss (%)	Slash (%)	Bare Ground (%)	Total Cover (%)	Grass Cover (%)	Forb Cover (%)	Shrub Cover (%)	Tree Cover (%)	Tree : Grass Shrub	Species Richness	SW Native Diversity*	SW Non-Native Diversity*	Jaccard similarity Index
Soil treatments														
p-values, 1 df	0.104	0.020	0.422	0.171	0.879	0.163	0.952	0.292	0.784	0.970	0.053	0.395	0.556	0.068
High disturbance	89.1	7.5	3.0	0.35	120.8	24.0	42.8	42.9	11.0	0.19	13.0	1.76	0.05	0.30
Root salvage	94.4	1.4	4.1	0.06	119.8	11.1	42.3	54.8	12.3	0.20	17.3	1.91	0.02	0.39
Standard errors	+/-1.5	+/-1.1	+/-0.7	+/-0.20	+/-3.1	+/-4.2	+/-4.0	+/-5.2	+/-2.4	+/-0.05	+/-1.0	+/-0.09	+/-0.03	+/-0.02

*Shannon Weiner index.

Table 2.11. Indicator and associated plant species for high disturbance (HI, n=5) and root salvage (RS, n=6) treatments and not-treated controls (CON, n=11) on northern Alberta boreal well sites. Associate species are shown as positively (+) or negatively (-) associated to groups.

	Indicator Score				Association				
Species	CON	HI	RS	p-value	CON	HI	RS	Score	p-value
Linnea borealis	0.992			0.001	+	-	-	0.992	0.005
Viburnum edule	0.970			0.001	+	-	-	0.970	0.005
Populus tremuloides	0.961			0.001	+	-	+	0.972	0.005
Aralia nudicaulis	0.945			0.001	+	-	-	0.945	0.005
Lycopodium annotinum	0.900			0.001	+	-	-	0.901	0.005
Cornus canadensis	0.863			0.001	+	-	+	0.920	0.010
Maianthemum canadense	0.758			0.001	+	+	-	0.826	0.035
Pyrola asarifolia	0.723			0.004	+	+	-	0.780	0.035
Picea glauca	0.708			0.003	+	-	+	0.848	0.025
Mitella nuda	0.682			0.001	+	-	+	0.966	0.005
Ribes triste	0.668			0.044					
Lonicera dioica	0.635			0.020	+	-	-	0.635	0.025
Rosa acicularis	0.522			0.011					
Equisetum sylvaticum		0.886		0.002	-	+	+	0.974	0.005
Carex sp.		0.772		0.044	-	+	+	0.986	0.005
Viola adunca		0.624		0.030					
Geum macrophyllum		0.566		0.040	-	+	-	0.566	0.030
Epilobium glandulosum		0.512		0.034					
Matteuccia struthiopteris			0.980	0.001	-	-	+	0.980	0.005
Halenia deflexa			0.743	0.008	-	-	+	0.734	0.010
Populus balsamifera			0.643	0.024					
Petasites palmatus			0.632	0.001					
Botrychium virginianum			0.600	0.023	-	-	+	0.601	0.020
Aster ciliatus			0.544	0.044					
Pyrola secunda					+	-	-	0.545	0.045
Rubus idaeus					-	+	+	0.982	0.005
Salix sp.					-	+	+	0.970	0.005
Calamagrostis canadensis					-	+	+	0.968	0.010
Epilobium angustifolium					-	+	+	0.925	0.020
Equisetum arvense					-	+	+	0.901	0.010
Vicia americana					-	+	+	0.885	0.005
Poa pratensis					-	+	+	0.885	0.005
Taraxacum officinale					-	+	+	0.799	0.005
Achillea sibirica					-	+	+	0.701	0.005
Achillea millefolium					-	+	+	0.672	0.010

Table 2.12. PerMANOVA results evaluating plant species compositional responses, and ANOVA results, means, and standard errors evaluating summary plant community characteristics between progressive (n=3) and separate (n=3) soil pile treatments, wood treatments and planting treatments on northern Alberta boreal well sites. Differences among least square means are indicated by different letters.

PerMANOVA	Df	Sum of Squares	Mean Squares	F Model	R2	Pr > F
Soil pile treatment	1	0.3917	0.3917	12.7	0.22	0.001
Wood treatment	1	0.0320	0.0320	1.0	0.02	0.390
Planting treatment	1	0.0506	0.0506	1.7	0.03	0.105
Site (random)	4	0.8522	0.2131	7.0	0.48	0.001
Soil * Wood	1	0.0261	0.0261	0.9	0.01	0.534
Soil * Planting	1	0.0260	0.0260	0.9	0.01	0.557
Wood * Planting	1	0.0204	0.0204	0.7	0.01	0.729
Soil*Wood*Planting	1	0.0208	0.0208	0.7	0.01	0.712
Residuals	12	0.3677	0.0306		0.21	
Total	23				1.00	

Means and ANOVA p-values: df	Litter (%)	Moss (%)	Slash (%)	Bare Ground (%)	Total Cover (%)	Grass Cover (%)	Forb Cover (%)	Shrub Cover (%)	Tree Cover (%)	Tree : Grass Shrub	Species Richness	SW Native Diversity*	SW Non-Native Diversity*	Jaccard Similarity Index
Soil pile treatments: 1	0.007	0.007	0.143	0.026	0.664	0.372	0.002	0.095	0.436	0.056	<0.001	<0.001	<0.001	0.095
Progressive	88.2	5.5	6.1	0.25	133.5	12.3	50.7	51.6	18.9	0.29	17.8	2.04	0.18	0.37
Separate	93.5	2.1	4.3	0.10	130.0	16.6	32.7	63.9	16.8	0.21	12.4	1.59	0.01	0.35
Standard errors	+/-5.2	+/-3.3	+/-1.8	+/-0.15	+/-3.5	+/-4.3	+/-18.0	+/-12.3	+/-26.1	+/-0.08	+/-0.4	+/-0.45	+/-0.12	+/-0.02
Wood treatments: 1	0.481	0.487	0.837	0.026	0.799	0.882	0.874	0.614	0.464	0.344	0.531	0.684	0.075	0.460
Spread	91.4	3.2	5.3	0.10	132.8	13.7	42.7	59.5	16.9	0.23	15.3	1.82	0.12	0.35
Windrow	90.3	4.4	5.1	0.25	130.8	15.2	40.7	56.0	18.8	0.27	14.9	1.81	0.06	0.36
Standard errors	+/-1.1	+/-1.2	+/-0.2	+/-0.15	+/-2.0	+/-1.6	+/-2.0	3.5	+/-2.0	+/-0.01	+/-1.0	+/-0.004	+/-0.06	+/-0.001
Planting treatments: 1	0.184	0.560	0.097	0.078	0.427	0.577	0.528	0.307	0.847	0.528	0.191	0.864	0.817	0.948
Planted	92.0	3.7	4.2	0.12	128.5	14.8	42.1	54.1	17.6	0.26	15.6	1.85	0.09	0.36
Non-planted	89.7	3.8	6.2	0.24	135.0	14.2	41.3	61.4	18.1	0.24	14.6	1.78	0.10	0.36
Standard errors	+/-2.2	+/-0.1	+/-2.0	+/-0.12	+/-6.5	+/-0.5	+/-0.8	+/-7.3	+/-1.6	+/-0.02	+/-4.5	+/-0.06	0.01	0.00
Soil pile * Planting: 1	0.176	0.136	0.235	0.920	0.133	0.974	0.071	0.156	0.007	0.036	0.244	0.201	0.553	0.470
Progressive planted	90.5	4.9	4.4	0.19	136.6	13.3	47.4a	53.1	22.9a	0.34a	17.9	2.02	0.17	0.37
Progressive non-planted	85.9	6.0	7.8	0.32	130.4	11.4	54.1a	50.1	14.9bc	0.23ab	17.8	2.06	0.19	0.36
Separate planted	93.4	2.3	4.0	0.04	120.5	16.2	36.9a	55.1	12.3c	0.18b	13.4	1.67	0.01	0.34
Separate non-planted	93.5	1.7	4.6	0.15	139.6	17.0	28.6a	72.7	21.3ab	0.24ab	11.5	1.51	0.00	0.35
Standard errors	+/-2.4	+/-1.0	+/-1.4	+/-0.01	+/-12.7	+/-1.4	+/-7.5	+/-10.3	+/-8.5	+/-0.08	+/-0.9	+/-0.10	+/-0.02	+/-0.01
Soil * Wood: 1	0.931	0.249	0.147	0.345	0.881	0.749	0.290	0.252	0.626	0.389	0.979	0.461	0.142	0.340
Wood * Planting: 1	0.598	0.502	0.286	0.110	0.383	0.654	0.917	0.327	0.224	0.358	0.680	0.214	0.595	0.901
Soil*Wood*Plant: 1	0.162	0.123	0.280	0.921	0.649	0.968	0.557	0.582	0.199	0.066	0.277	0.028	0.375	0.290
Site (random): 4	0.011	0.002	0.344	0.698	0.870	0.034	<0.001	0.248	0.008	0.104	<0.001	0.001	<0.001	<0.001

*Shannon Weiner index.

Table 2.13. Indicator and associated plant species for progressive (P, n=3) and separate (S, n=3) soil pile treatments and not-treated controls (CON, n=6) on northern Alberta boreal well sites. Associate species are shown as positively (+) or negatively (-) associated to groups.

	Indicator Score				Association				
Species	CON	P	S	p-value	CON	P	S	Score	p-value
Viburnum edule	0.960			0.003	+	-	-	0.960	0.015
Populus tremuloides	0.941			0.002					
Linnea borealis	0.938			0.002	+	+	-	0.996	0.020
Aralia nudicaulis	0.931			0.002	+	-	-	0.931	0.045
Pyrola asarifolia	0.896			0.003					
Picea glauca	0.896			0.002					
Maianthemum canadense	0.865			0.003					
Cornus canadensis	0.846			0.004	+	+	-	0.960	0.045
Lonicera dioica	0.836			0.030					
Lathyrus venosus		1.000		0.007	-	+	-	1.000	0.010
Trifolium hybridium		1.000		0.007	-	+	-	1.000	0.010
Agropyron trachycaulum		0.998		0.007	-	+	-	0.998	0.010
Halenia deflexa		0.967		0.013	-	+	-	0.966	0.010
Taraxacum officinale		0.910		0.024	-	+	-	0.910	0.010
Sonchus arvensis		0.895		0.030	-	+	-	0.895	0.025
Viola canadensis		0.848		0.016					
Bromus ciliatus		0.828		0.048	-	+	-	0.828	0.040
Carex sp.		0.824		0.037					
Achillea sibirica		0.718		0.030	-	+	-	0.716	0.035
Equisetum sylvaticum		0.694		0.046					
Betula papyrifera		0.398		0.018					
Geranium bicknellii			0.974	0.011	-	-	+	0.947	0.010
Potentilla norvegica			0.923	0.026	-	-	+	0.924	0.025
Salix sp.					-	+	+	0.992	0.010
Calamagrostis canadensis					-	+	+	0.968	0.050
Rubus idaeus					-	+	+	0.962	0.010
Viola canadensis					-	+	+	0.962	0.035
Agrostis stolonifera					-	+	+	0.953	0.010
Vicia Americana					-	+	+	0.947	0.050
Matteuccia struthiopteris					-	+	+	0.832	0.040

Table 2.14. PerMANOVA results evaluating plant species compositional responses and two-way ANOVA results, means and standard errors evaluating summary plant community characteristics between mulch (n=3), spread (n=2) and windrowed (n=2) slash treatments, and planting treatments, within the low soil disturbance sites on northern Alberta boreal well sites. Differences among least square means are indicated by different letters.

PerMANOVA	Df	Sum of Squares	Mean Squares	F Model	R2	Pr > F
Wood treatment	2	0.395	0.198	2.8	0.22	0.011
Planting treatment	1	0.099	0.099	1.4	0.06	0.184
Site (random)	3	0.855	0.285	4.1	0.48	0.045
Wood * Planting	2	0.077	0.039	0.6	0.04	0.673
Residuals	5	0.350	0.070		0.20	
Total	13	1.776			1.00	

Means and ANOVA	Litter (%)	Moss (%)	Slash (%)	Bare Ground (%)	Total Cover (%)	Grass Cover (%)	Forb Cover (%)	Shrub Cover (%)	Tree Cover (%)	Tree : Grass Shrub	Species Richness	SW Native Diversity*	SW Non-Native Diversity*	Jaccard Similarity Index
Wood treatments														
p-values, 2 df	0.065	0.693	<0.001	0.106	0.064	0.221	0.060	0.279	0.794	0.754	0.763	0.178	0.620	0.666
Mulch	87.9a	9.7	2.5b	0.01	129.3b	21.0	35.1b	47.8	25.4	0.46	14.3	1.78	0.04	0.36
Spread slash	82.6ab	8.0	9.2a	0.18	156.1a	27.9	63.6a	39.5	25.1	0.38	14.4	1.98	0.02	0.39
Windrowed slash	77.2b	6.6	16.0a	0.15	148.7ab	13.8	58.5a	45.3	31.1	0.55	15.1	2.03	0.03	0.36
Standard errors	+/-7.4	+/-2.1	+/-9.4	+/-0.08	+/-19.7	+/-8.9	+/-21.7	+/-5.8	+/-4.4	+/-0.05	+/-0.6	+/-0.09	+/-0.01	+/-0.02
Planting treatments														
p-values, 1 df	0.091	0.092	0.908	0.064	0.508	0.512	0.956	0.028	0.800	0.615	0.901	0.931	0.944	0.595
Planted	86.3	5.4	8.3	0.14	139.9	22.8	49.7	39.6	27.9	0.48	14.6	1.92	0.03	0.37
Non-planted	80.3	11.3	8.2	0.05	145.1	19.1	50.2	49.8	26.0	0.44	14.6	1.90	0.03	0.36
Standard errors	+/-4.9	+/-4.9	+/-0.1	+/-0.03	+/-4.4	+/-3.1	+/-0.4	+/-8.6	+/-1.6	+/-0.03	+/-0.02	+/-0.03	+/-0.001	+/-0.01
Wood * Planting														
p-values, 2 df	0.898	0.605	0.344	0.122	0.210	0.691	0.296	0.690	0.558	0.556	0.217	0.361	0.380	0.929
Site (random): 3 df	0.022	0.033	0.049	0.263	0.008	0.080	0.150	0.004	0.632	0.382	0.210	0.095	0.099	0.043

*Shannon Weiner index

Table 2.15. Summary of significant (p≤0.05) indicator and associated plant species for each of the mulch (MUL, n=3), spread slash (SP, n=2) and windrowed slash (WIN, n=2) treatments and indicator and associated species for planted (P, n=7) and non-planted (NP, n=7) treatments within the low disturbance soil treatment and not-treated controls (CON, n=5), on northern Alberta boreal well sites. Associate species are shown as positively (+) or negatively (-) associated to groups.

Wood Treatment	Indicator Score					Association					
Species	CON	MUL	SP	WIN	p-value	CON	MUL	SP	WIN	Score	p-value
Populus tremuloides	0.559				0.003						
Epilobium glandulosum				0.917	0.043						
Cirsium arvense						-	+	-	-	0.666	0.045
Geum rivale						-	-	+	-	0.799	0.050
Bromus ciliatus						-	-	+	+	0.925	0.020
Taraxacum officinale						-	+	+	+	1.000	0.010
Rubus idaeus						-	+	+	+	1.000	0.010
Betula papyrifera						-	+	+	+	1.000	0.015
Salix sp.						-	+	+	+	1.000	0.015
Epilobium angustifolium						-	+	+	+	0.990	0.015
Achillea millefolium						-	+	+	+	0.972	0.005
Galium triflorum						-	+	+	+	0.958	0.050

Planting Treatment	Indicator Score				Association				
Species	CON	P	NP	p-value	CON	P	NP	Score	p-value
Ledum groenlandicum	0.699			0.009	+	-	-	0.698	0.025
Linnea borealis	0.659			0.005					
Populus tremuloides	0.659			0.001					
Lycopodium annotinum	0.652			0.013	+	-	-	0.652	0.025
Picea mariana	0.600			0.011	+	-	-	0.600	0.010
Trientalis borealis	0.524			0.046					
Pyrola secunda	0.523			0.048	+	-	-	0.523	0.030
Rubus idaeus			0.608	0.002	-	+	+	1.000	0.005
Galium triflorum			0.588	0.013					
Trifolium pratense					-	-	+	0.459	0.035
*Taraxacum officinale**			0.579	0.045	-	+	+	1.000	0.005
Salix sp.*			0.549	0.030	-	+	+	1.000	0.005
Calamagrostis canadensis					-	+	+	0.994	0.005
Equisetum sylvaticum					-	+	+	0.988	0.005
Vicia Americana					-	+	+	0.976	0.005
Achillea millefolium					-	+	+	0.954	0.005
*Epilobium angustifolium**		0.567		0.030	-	+	+	0.913	0.010
Galium triflorum					-	+	+	0.872	0.020
Betula papyrifera					-	+	+	0.857	0.020
*Agropyron trachycaulum**			0.449	0.050					

*Identified as indicator species with permutated species data.

Table 2.16. PerMANOVA results evaluating plant species compositional responses and two-way ANOVA results, means and standard errors evaluating summary plant community characteristics between deep (n=18) and shallow (n=18) mulch depth treatments and planting treatments, in low soil disturbance sites on northern Alberta boreal well sites.

PerMANOVA	Df	Sum of Squares	Mean Squares	F Model	R2	Pr > F
Mulch depth	1	0.144	0.144	1.6	0.03	0.119
Planting	1	0.316	0.316	3.5	0.06	0.007
Plot	2	0.123	0.062	0.7	0.02	0.783
Site (random)	2	2.418	1.209	13.5	0.44	0.001
Depth * Planting	1	0.099	0.099	1.1	0.02	0.356
Plot * Site	4	0.255	0.064	0.7	0.05	0.831
Residuals	24	2.148	0.089		0.39	
Total	35	5.504			1.00	

Means and ANOVA	Litter (%)	Moss (%)	Slash (%)	Bare Ground (%)	Total Cover (%)	Grass Cover (%)	Forb Cover (%)	Shrub Cover (%)	Tree Cover (%)	Tree : Grass Shrub	Species Richness	SW Native Diversity*	SW Non - Native Diversity*	Jaccard Similarity Index
Wood treatments														
p-values, 1df	0.082	0.026	0.524	0.551	0.470	0.388	0.030	0.787	0.010	0.234	0.980	0.658	0.012	0.276
Deep	62.7	15.4	20.0	1.8	81.7	5.0	28.5	30.1	18.2	0.99	10.2	1.55	0.09	0.29
Shallow	72.0	9.3	17.3	1.4	87.4	6.6	21.7	29.2	30.0	4.02	10.2	1.50	0.02	0.31
Standard errors	+/-4.7	+/-3.1	+/-1.3	+/-0.22	+/-2.8	+/-0.8	+/-3.4	+/-0.4	+/-5.9	+/-1.5	+/-0.01	+/-0.02	+/-0.04	+/-0.02
Planting treatments														
p-values, 1df	0.819	0.447	0.447	1.000	0.942	0.899	0.301	0.031	0.060	0.312	0.749	0.582	0.629	0.933
Planted	67.9	11.4	19.1	1.63	84.3	5.9	24.2	25.9	28.3	3.79	10.4	1.56	0.06	0.31
Non-planted	66.8	13.4	18.2	1.63	84.9	5.7	26.0	33.3	19.9	1.22	10.0	1.50	0.05	0.31
Standard errors	+/-0.819	+/-1.0	+/-0.4	+/-0.00	+/-0.3	+/-0.1	+/-0.9	+/-3.7	+/-4.2	+/-1.3	+/-0.2	+/-0.03	+/-0.01	+/-0.001
Depth * Planting														
p-values, 1 df	0.092	0.171	0.273	0.393	0.076	0.298	0.074	0.735	0.325	0.519	0.199	0.205	0.702	0.447
Deep planted	67.8	12.6	18.1	1.5	88.6a	6.1	32.2a	25.8	24.5	1.46	10.8	1.65	0.10	0.30
Deep non-planted	57.6	18.3	21.9	2.2	74.9a	4.0	24.8a	34.3	11.8	0.52	9.7	1.45	0.08	0.28
Shallow planted	68.1	5.8	20.1	1.7	80.0a	5.8	16.2a	26.0	32.0	6.12	9.3	1.46	0.02	0.31
Shallow non-planted	75.9	7.4	94.8	1.1	94.8a	7.4	27.2a	32.3	27.9	1.92	11.1	1.54	0.02	0.34
Standard errors	+/-10.1	+/-5.3	+/-0.9	+/-0.6	+/-0.8	+/-2.4	+/-10.6	+/-6.5	+/-0.8	+/-0.60	+/-2.2	+/-0.18	+/-0.05	+/-0.30
Plot: 1	0.791	0.672	0.990	0.681	0.870	0.364	0.105	0.208	0.087	0.789	0.578	0.200	0.474	0.376
Plot * Site: 2	0.791	0.206	0.919	0.879	0.268	0.905	0.764	0.028	0.452	0.982	0.616	0.614	0.873	0.793
Site (random): 2	0.005	0.851	0.001	0.855	<0.001	0.007	0.001	<0.001	0.015	0.191	0.001	<0.001	0.021	<0.001

*Shannon Weiner index.

Table 2.17. Indicator and associated plant species for deep (D, n=18) and shallow (S, n=18) slash and planted (P, n=18) and non-planted (NP, n=18) treatments and not-treated controls (CON and PCON, respectively, n=18) at mulch depth treatment on northern Alberta boreal well sites. Indicator values represent strength of a species affinity to a site group. Association scores represent strength of a species affinity for a group of sites. Significant species associations (p≤0.05) are shown as positively (+) or negatively (-) associated to groups.

	Indicator Score						p-value (s)		Association						Score (s)	
Species	CON	PCON	D	S	P	NP	CON / DS	CON / PNP	CON	PCON	D	S	P	NP	CON / DS	CON / PNP
Picea mariana	0.667	0.667					0.001	0.001	+	+	-	-	-	-	0.665	0.665
Pyrola asarifolia	0.649	0.649					0.002	0.002	+	+	-	-	-	-	0.648	0.648
Linnea borealis	0.560	0.560					0.002	0.002	+	+	-	-	-	-	0.643	0.643
Abies balsamea	0.556	0.556					0.001	0.001	+	+	-	-	-	-	0.555	0.555
Equisetum arvense	0.490	0.490					0.002	0.002	+	+	-	-	-	-	0.490	0.490
Maianthemum canadense	0.444	0.444					0.002	0.002	+	+	-	-	-	-	0.445	0.445
Trientalis borealis	0.444	0.444					0.036	0.036								
Aralia nudicaulis	0.437	0.437					0.002	0.002	+	+	-	-	-	-	0.437	0.437
Mitella nuda	0.425	0.425					0.006	0.006	+	+	-	-	-	-	0.425	0.425
Rosa acicularis	0.358	0.358					0.047	0.047		+			-	+		0.513
Lycopodium annotinum	0.326	0.326					0.009	0.009	+	+	-	-	-	-	0.326	0.326
Ribes sp.	0.222	0.222					0.040	0.040	+	+	-	-	-	-	0.222	0.222
Mertensia paniculata	0.218	0.218					0.030	0.030	+	+	-	-			0.218	0.218
Epilobium angustifolium			0.506				0.008									
Populus balsamifera			0.299		0.444		0.046	0.006	-	-	+	-	+	-	0.299	0.445
Carex sp.				0.509	0.585		0.024	0.004	-	-	+	+	+	+	0.795	0.796
Aster ciliolatus						0.555		0.043	-	-	+	+	+	+	0.867	0.867
Taraxacum officinale									-		+	+			0.579	
Galium triflorum					0.324			0.041		-			+	-		0.324
Achillea sibirica					0.297			0.041		-			+	-		0.297
Achillea millefolium						0.483		0.022								
Epilobium glandulosum						0.303		0.046								
Hieracium umbellatum						0.283		0.046		-			+	+		0.293
Lonicera villosa										-			-	+		0.222
Larix laricina										-			-	+		0.222
Taraxacum officinale										-			+	+		0.579
Picea glauca										+			+	-		0.534

Table 2.18. PerMANOVA results evaluating plant species compositional responses and two-way ANOVA results, means and standard errors evaluating summary plant community characteristics between spread (n=3) and windrowed (n=3) slash treatments, and planting treatments in progressive soil pile treatment sites on northern Alberta boreal well sites. Differences among least square means are indicated by different letters.

PerMANOVA	Df	Sum of Squares	Mean Squares	F Model	R2	Pr > F
Wood treatment	1	0.0143	0.0143	0.5	0.02	0.770
Planting treatment	1	0.0291	0.0291	1.1	0.05	0.337
Site random)	2	0.4039	0.2019	7.7	0.64	0.001
Wood * Planting	1	0.0234	0.0234	0.9	0.04	0.505
Residuals	6	0.1573	0.0262		0.25	
Total	11	0.6278			1.00	

Means and ANOVA	Litter (%)	Moss (%)	Slash (%)	Bare Ground (%)	Total Cover (%)	Grass Cover (%)	Forb Cover (%)	Shrub Cover (%)	Tree Cover (%)	Tree : Grass Shrub	Species Richness	SW Native Diversity*	SW Non-Native Diversity*	Jaccard Similarity Index
Wood treatment														
p-values, 2df	0.615	0.213	0.114	0.099	0.950	0.811	0.169	0.599	0.099	0.937	0.566	0.543	0.123	0.376
Spread	88.7	4.1	7.1	0.15	133.9	12.4	53.7	49.2	18.5	0.29	18.0	2.06	0.23	0.36
Windrow	87.7	6.8	5.1	0.36	133.1	12.3	47.7	53.9	19.2	0.29	17.6	2.02	0.13	0.38
Standard errors	+/-1.8	+/-1.3	+/-0.9	+/-0.18	+/-10.1	+/-5.1	+/-4.0	+/-16.8	+/-3.3	+/-0.06	+/-0.55	+/-0.09	+/-0.05	+/-0.01
Planting treatment														
p-values, 2df	0.059	0.498	0.018	0.304	0.651	0.665	0.185	0.899	0.006	0.037	0.988	0.689	0.681	0.706
Planted	90.5	4.9	4.4	0.19	136.6	13.3	47.3	53.1	22.9	0.34	17.9	2.02	0.17	0.37
Non-planted	85.9	6.0	7.8	0.32	130.4	11.4	54.1	50.1	14.9	0.23	17.8	2.06	0.19	0.36
Standard errors	+/-1.8	+/-2.6	+/-1.3	+/-0.01	+/-4.5	+/-0.7	+/-2.8	+/-7.6	+/-1.4	+/-0.03	+/-1.1	+/-0.09	+/-0.06	+/-0.03
Wood * Planting														
p-values, 1 df	0.135	0.512	0.056	0.808	0.091	0.086	0.756	0.022	0.016	0.038	0.127	0.196	0.557	0.499
Spread planted	92.7	3.1	4.1b	0.13	138.8	12.7	47.8	52.3a	25.9a	0.39a	17.9	2.03	0.20	0.36
Spread non-planted	84.7	5.1	10.0a	0.16	129.1	12.1	59.7	46.2a	11.2b	0.18b	18.2	2.09	0.27	0.36
Windrow planted	88.4	6.8	4.6b	0.25	134.5	13.9	46.9	53.9a	19.8ab	0.29ab	17.8	2.02	0.14	0.39
Windrow non-planted	87.1	6.9	5.5b	0.48	131.7	10.6	48.5	53.9a	18.7ab	0.29ab	17.4	2.02	0.12	0.37
Standard errors	+/-0.04	+/-0.1	+/-1.2	+/-0.07	+/-0.02	+/-0.02	+/-0.01	+/-0.01	+/-0.1	+/-0.1	+/-0.01	+/-0.02	+/-0.03	+/-0.01
Site (random), 2 df	0.007	0.004	0.155	0.769	0.879	0.806	<0.001	0.326	0.002	0.047	0.140	0.012	0.004	0.493

*Shannon Weiner index.

Table 2.19. PerMANOVA results evaluating plant species compositional responses and two-way ANOVA results, means and standard errors evaluating summary plant community characteristics between spread (n=3) and windrowed (n=3) slash treatments, and planting treatments in separate soil pile treatment sites on northern Alberta boreal well sites. Differences among least square means are indicated by different letters.

PerMANOVA	Df	Sum of Squares	Mean Squares	F Model	R2	Pr > F
Wood treatment	1	0.0439	0.0439	1.3	0.06	0.271
Planting treatment	1	0.0476	0.0476	1.4	0.06	0.190
Site random)	2	0.4484	0.2242	6.4	0.58	0.001
Wood * Planting	1	0.0178	0.0178	0.5	0.02	0.800
Residuals	6	0.2104	0.0351		0.27	
Total	11	0.7680			1.00	

Means and ANOVA	Litter (%)	Moss (%)	Slash (%)	Bare Ground (%)	Total Cover (%)	Grass Cover (%)	Forb Cover (%)	Shrub Cover (%)	Tree Cover (%)	Tree : Grass Shrub)	Species Richness	SW Native Diversity*	SW Non-Native Diversity*	Jaccard Similarity Index
Wood treatments														
p-values, 1df	0.628	0.744	0.475	0.117	0.739	0.864	0.499	0.072	0.434	0.299	0.803	0.695	-	0.918
Spread	94.1	2.3	3.6	0.05	131.65	15.0	31.7	69.8	15.2	0.18	12.6	1.57	0.01	0.35
Windrow	92.8	2.0	5.1	0.15	128.4	18.2	33.7	58.1	18.4	0.25	12.3	1.61	0.00	0.35
Standard errors	+/-3.3	+/-0.8	+/-2.5	+/-0.02	+/-13.2	+/-5.0	+/-7.9	+/-6.2	+/-4.1	0.06	+/-0.26	+/-0.05	-	+/-0.01
Planting treatment														
p-values, 1df	0.998	0.178	0.765	0.076	0.122	0.413	0.173	0.019	0.101	0.342	0.073	0.163	-	0.460
Planted	93.4	2.5	4.0	0.04	120.5	16.2	36.9	55.1	12.3	0.18	13.4	1.67	0.01	0.34
Non-planted	93.5	1.7	4.6	0.15	139.6	17.0	28.6	72.7	21.3	0.24	11.5	1.50	0.00	0.35
Standard errors	+/-2.8	+/-1.0	1.8	+/-0.08	+/-10.3	+/-7.5	+/-6.5	+/-7.9	+/-6.0	+/-0.08	+/-1.5	+/-0.16	-	+/-0.01
Wood * Planting, 1df	0.556	0.155	0.994	0.076	0.305	0.592	0.656	0.084	0.984	0.544	0.243	0.750	-	0.378
Site (random), 2df	0.390	0.239	0.472	0.240	0.630	0.043	0.183	0.503	0.548	0.389	0.001	0.011	-	<0.001

*Shannon Weiner index

Table 2.20. Summary of significant (p≤0.05) indicator and associated plant species for spread slash treatments in progressive and separate soil pile treatments (PS, SS, respectively, n=3) and windrowed slash treatments within progressive and separate soil pile treatments (PW, SW, respectively, n=3) and not-treated progressive and separate treatment site controls (PCON, SCON, respectively, n=3) on northern Alberta boreal well sites. Indicator values represent strength of a species affinity to a site group. Association scores represent strength of a species affinity for a group of sites. Significant species associations (p≤0.05) are shown as positively (+) or negatively (-) associated to groups.

	Indicator Score						p-value (s)		Association						Score (s)	
Species	PCON	SCON	PS	PW	SS	SW	PCON	SCON	PCON	SCON	PS	PW	SS	SW	PCON	SCON
Viburnum edule	0.968	0.955					0.037	0.033	+	+	-	-	-	-	0.968	0.954
Elymus innovatus	0.953						0.035		+		-	-			0.953	
Aralia nudicaulis	0.941	0.922					0.027	0.038	+		-	-			0.941	
Pyrola asarifolia	0.933						0.049									
Populus tremuloides	0.928	0.957					0.039	0.043								
Linnea borealis	0.923	0.989					0.037	0.045		+			-	-		0.986
Lonicera dioica	0.909						0.043		+		-	-			0.908	
Maianthemum canadense	0.896	0.829					0.035	0.040								
Cornus canadensis	0.826	0.032					0.034	0.032								
Picea glauca	0.806	0.949					0.044	0.039								
Betula papyrifera				0.558			0.050									
Equisetum arvense					0.940			0.025		-			+	+		0.994
Viola canadensis					0.432			0.025								
Agropyron trachycaulum									-		+	+			1.000	
Viola canadensis									-		+	+			1.000	
Rubus idaeus									-	-	+	+	+	+	1.000	0.937
Salix sp.									-	-	+	+	+	+	0.988	1.000
Taraxacum officinale									-		+	+			0.984	
Calamagrostis canadensis									-	-	+	+	+	+	0.984	0.964
Agrostis stolonifera									-		+	+			0.935	
Geranium bicknellii										-			+	+		1.000
Vicia americana										-			+	+		0.962

Table 2.21. Indicator and associated plant species for spread (S, n=6) and windrowed (W, n=6) slash treatments and planted (P, n=6) and non-planted (NP, n=6) treatments and not-treated controls (CON and PCON, respectively, n=6) at soil pile treatment on northern Alberta boreal well sites. Indicator values represent strength of a species affinity to a site group. Association scores represent strength of a species affinity for a group of sites. Significant species associations (p≤0.05) are shown as positively (+) or negatively (-) associated to groups.

	Indicator Score						p-value (s)		Association						Score (s)	
Species	CON	PCON	S	W	P	NP	CON / SW	CON / PNP	CON	PCON	S	W	P	NP	CON / SW	CON / PNP
Viburnum edule	0.960	0.960					0.001	0.001	+	+	-	-	-	-	0.960	0.960
Populus tremuloides	0.941	0.941					0.001	0.001	+	+	-	-	-	-	0.941	0.941
Linnea borealis	0.938	0.938					0.002	0.003	+	+	-	-	-	-	0.938	0.939
Aralia nudicaulis	0.931	0.931					0.001	0.001	+	+	-	-	-	-	0.931	0.931
Pyrola asarifolia	0.896	0.896					0.003	0.001	+	+	-	-	-	-	0.895	0.895
Picea glauca	0.896	0.896					0.001	0.001	+	+	-	+	-	+	0.966	0.949
Maianthemum canadense	0.865	0.865					0.001	0.001								
Cornus canadensis	0.846	0.846					0.002	0.003								
Lonicera dioica	0.836	0.836					0.004	0.004	+	+	-	-	-	-	0.835	0.835
Pyrola secunda	0.763	0.763					0.007	0.010	+	+	-	-	-	-	0.764	0.764
Lycopodium annotinum	0.667	0.667					0.016	0.013	+	+	-	-	-	-	0.666	0.666
Orchid sp.	0.667	0.667					0.013	0.009	+	+	-	-	-	-	0.666	0.666
Ledum groenlandicum	0.666	0.666					0.016	0.020	+	+	-	-	-	-	0.666	0.666
Vaccinium myrtilloides	0.646	0.646					0.023	0.020	+	+	-	-	-	-	0.646	0.646
Elymus innovatus	0.637	0.637					0.027	0.029								
Equisetum scirpoides	0.611	0.611					0.015	0.026	+	+	-	-	-	-	0.612	0.612
Aquilegia brevistyla			0.620				0.040		-		+	-			0.619	
Galium triflorum			0.518				0.036									
Salix sp.					0.562			0.024	-	-	+	+	+	+	0.992	0.992
Carex sp.									-	-	+	+	+	+	0.970	0.970
Calamagrostis canadensis									-	-	+	+	+	+	0.968	0.968
Rubus idaeus						0.520		0.037	-	-	+	+	+	+	0.962	0.962
Viola canadensis									-	-	+	+	+	+	0.962	0.962
Vicia Americana									-	-	+	+	+	+	0.947	0.947
Equisetum arvense									-		+	+			0.922	
Agrostis stolonifera									-	-	+	+	+	+	0.874	0.874
Taraxacum officinale									-	-	+	+	+	+	0.821	0.821
Matteuccia struthiopteris									-		+	+			0.762	
Geum aleppicum					0.776			0.003	-	-	+	+	+	-	0.666	0.776
Vicia americana						0.573		0.033								
Bromus ciliatus										-			+	+		0.738

Table 2.22. Summary of significant (p≤0.05) indicator and associated plant species for planted and non-planted treatments within spread slash treatments (PS, NPS, respectively, n=3) and not-treated controls (SCON, n=3) and planted and non-planted treatments within windrowed slash treatments (PW, NPW, respectively, n=3) and not-treated controls (WCON, n=3) within progressive and separate soil pile treatments on northern Alberta boreal well sites. Indicator values represent strength of a species affinity to a site group. Association scores represent strength of a species affinity for a group of sites. Significant species associations (p≤0.05) are shown as positively (+) or negatively (-) associated to groups.

Progressive	Indicator Score						p-value (s)		Association						Score (s)	
Species	SCON	WCON	PS	NPS	PW	NPW	SCON / S	WCON / W	SCON	WCON	PS	NPS	PW	NPW	SCON / S	WCON / W
Viburnum edule	0.971	0.965					0.039	0.032	+		-	-			0.971	
Pyrola secunda	0.968						0.027		+		-	-			0.968	
Pyrola asarifolia	0.963	0.905					0.038	0.035	+		-	-			0.963	
Aralia nudicaulis	0.955	0.927					0.044	0.045	+		-	-			0.955	
Populus tremuloides	0.943	0.912					0.049	0.031								
Elymus innovatus	0.934	0.973					0.035	0.036	+		-	-			0.934	
Linnea borealis	0.898	0.951					0.040	0.033								
Maianthemum canadense	0.890	0.902					0.033	0.036								
Picea glauca	0.867	0.753					0.033	0.035								
Cornus canadensis	0.850	0.804					0.039	0.034								
Lonicera dioica		0.930					0.041									
Bromus ciliatus					0.777			0.039		-			+	+		0.968
Agropyron trachycaulum									-	-	+	+	+	+	1.000	1.000
Viola canadensis									-	-	+	+	+	+	1.000	1.000
Rubus idaeus									-	-	+	+	+	+	1.000	1.000
Salix sp.									-	-	+	+	+	+	0.984	0.995
Calamagrostis canadensis									-	-	+	+	+	+	0.974	0.994
Separate	Indicator Score						p-value (s)		Association						Score (s)	
Species	SCON	WCON	PS	NPS	PW	NPW	SCON / S	WCON / W	SCON	WCON	PS	NPS	PW	NPW	SCON / S	WCON / W
Linnea borealis	0.973						0.036		+	+	-	-	-	-	0.973	1.000
Viburnum edule	0.968	0.942					0.034	0.036	+	+	-	-	-	-	0.968	0.889
Picea glauca	0.963	0.935					0.030	0.026								
Populus tremuloides	0.938	0.976					0.036	0.030	+		-	-			0.937	
Aralia nudicaulis	0.909	0.935					0.050	0.029								
Cornus canadensis	0.905	0.863					0.037	0.042								
Maianthemum canadense	0.843	0.816					0.033	0.027								
Equisetum arvense			0.962				0.033									
Viola canadensis			0.511				0.040									
Pyrola asarifolia		0.889						0.037		+			-	-		0.889
Alnus crispa						0.680		0.020		-			-	+		0.681
Salix sp.									-	-	+	+	+	+	1.000	1.000
Carex sp.									-		+	+			0.968	
*Rubus idaeus**						0.530		0.040		-			+	+		0.965

*Species identified as indicators with permuted data.

Table 2.23. Indicator and associated plant species for planted (P, n=10) and non-planted (NP, n=10) treatments within high and low soil disturbance treatments and not-treated controls (CON, n=10) at well sites in the boreal region of Alberta. Associate species are shown as positively (+) or negatively (-) associated to groups.

	Indicator Score				Association				
Species	CON	P	NP	p-value	CON	P	NP	Score	p-value
Mitella nuda	0.905			0.001	+	-	-	0.904	0.005
Lycopodium annotinum	0.900			0.001	+	-	-	0.889	0.005
Viburnum edule	0.883			0.001	+	-	-	0.884	0.005
Linnea borealis	0.879			0.001	+	-	-	0.876	0.005
Populus tremuloides	0.821			0.001					
Maianthemum canadense	0.742			0.001					
Aralia nudicaulis	0.710			0.004	+	-	-	0.712	0.010
Cornus canadensis	0.640			0.001					
Pyrola asarifolia	0.486			0.045					
Abies balsamea	0.483			0.016	+	-	-	0.483	0.025
Pyrola secunda	0.440			0.017	+	-	-	0.439	0.015
Picea mariana	0.400			0.031	+	-	-	0.399	0.030
Carex sp.		0.534		0.033	-	+	+	0.988	0.005
Populus balsamifera		0.541		0.017					
Equisetum sylvaticum			0.554	0.033					
Salix sp.			0.547	0.026					
Epilobium glandulosum			0.532	0.016	-	-	+	0.479	0.010
Rubus idaeus					-	+	+	0.976	0.005
Salix sp.					-	+	+	0.949	0.005
Epilobium angustifolium					-	+	+	0.949	0.005
Equisetum arvense					-	+	+	0.942	0.010
*Calamagrostis canadensis**			0.569	0.040	-	+	+	0.870	0.005
Vicia Americana					-	+	+	0.817	0.010
Galium triflorum					-	+	+	0.702	0.010
Taraxacum officinale					-	+	+	0.697	0.005
Achillea sibirica					-	+	+	0.650	0.015

*Species identified as indicators with permuted data.

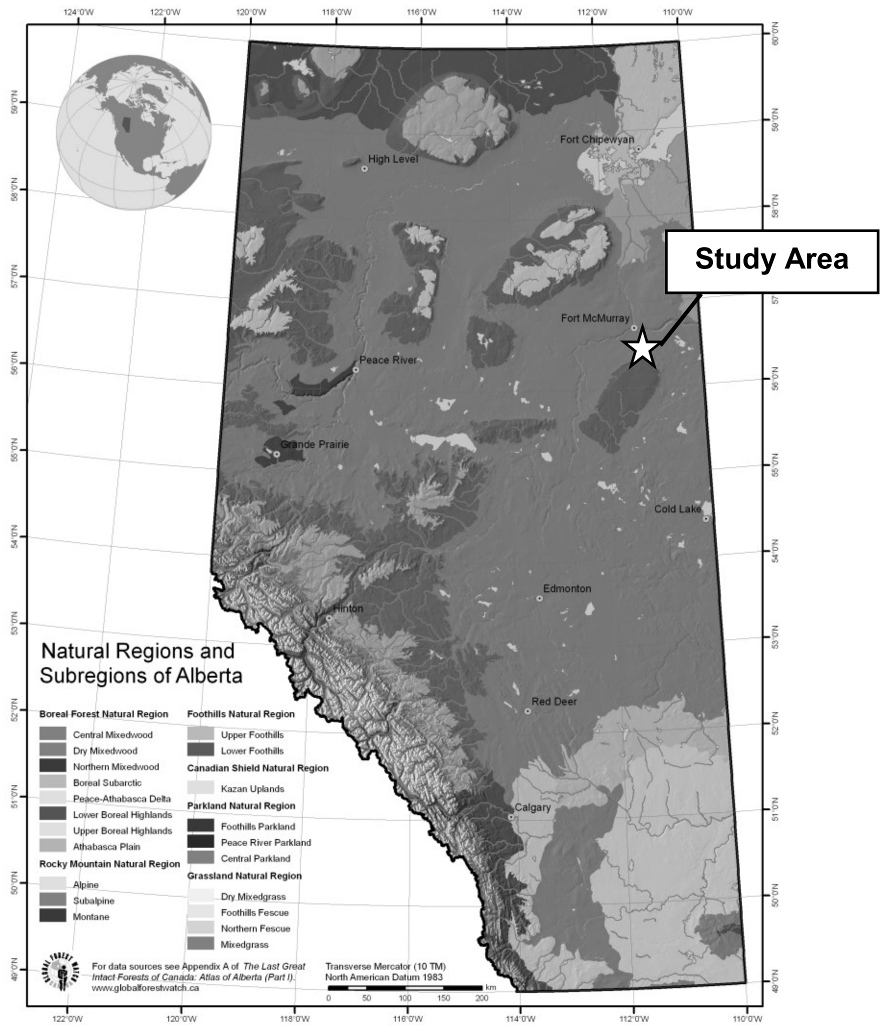

Figure 2.1. The natural subregions of Alberta, adapted from Global Forest Watch Canada (2005).

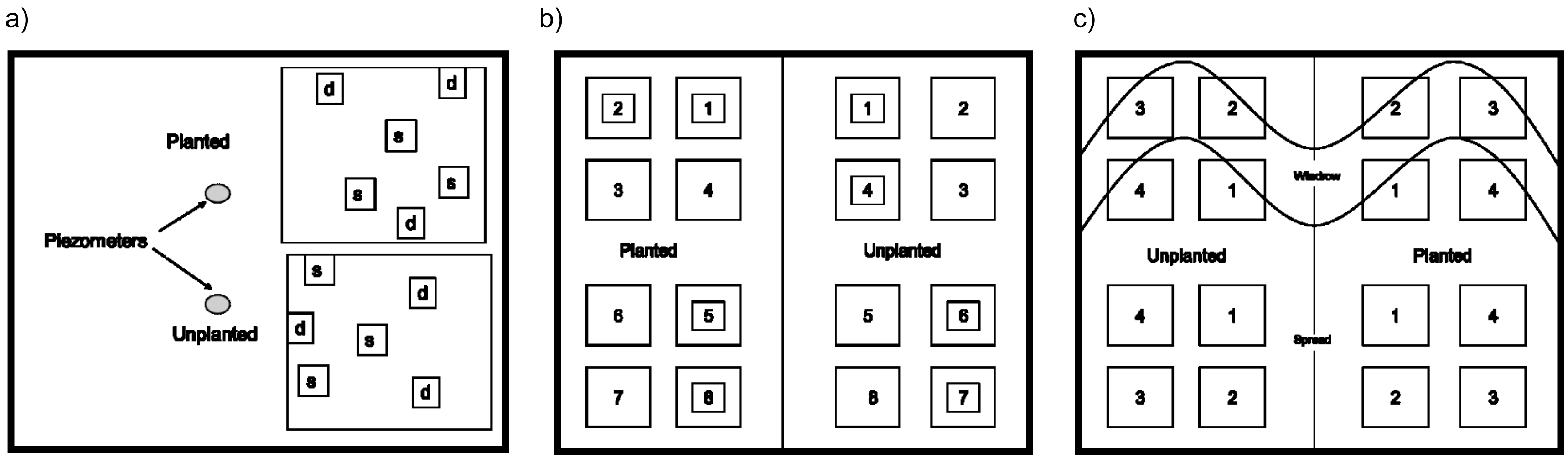

Figure 2.2. Site schematic for a) shallow [s] and deep [d] mulch plots within mulch depth treatment sites; b) a site with one woody debris treatment, further split into planted and non-planted treatments; c) a site with two woody debris treatments and planted and non-planted treatments.

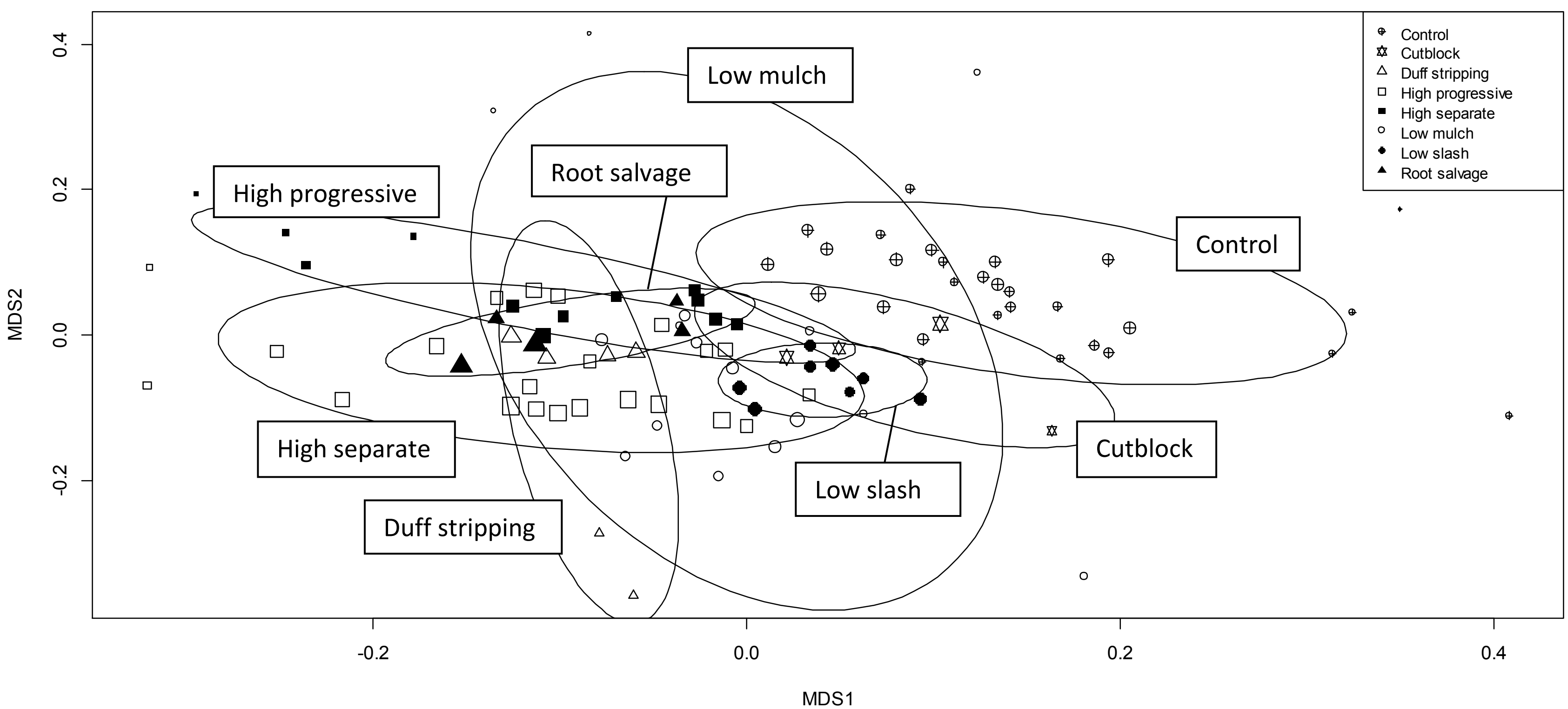

Figure 2.3. NMDS ordination plot depicting species composition of study plant communities (except deep and shallow mulch) contrasting low through high soil disturbance treatments from well sites, cutblocks and adjacent non-treated controls in northern Alberta. Size of symbol increases with species richness. Ordination stress=0.18.

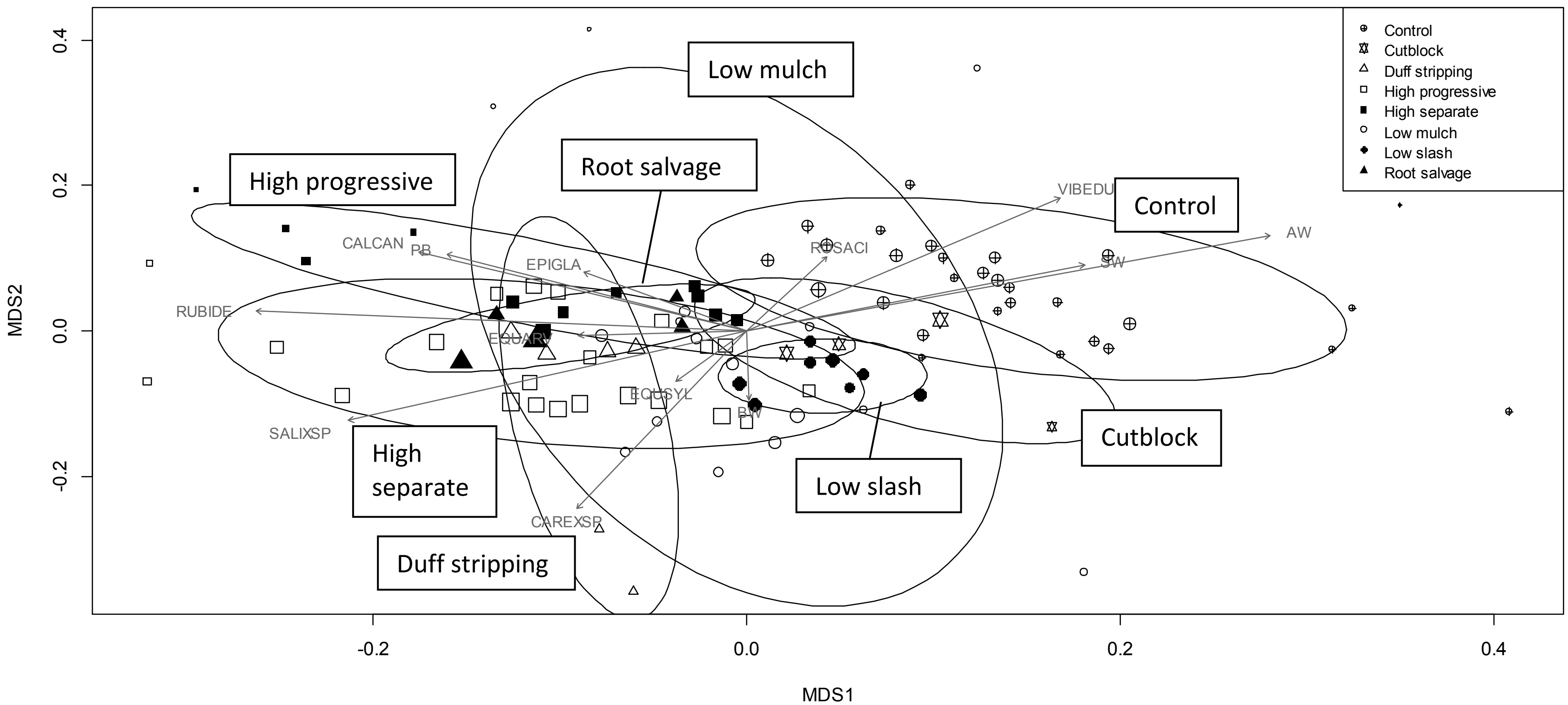

Figure 2.4. NMDS ordination plot depicting species composition in study plant communities (except deep and shallow mulch) contrasting low through high soil disturbance treatments from well sites, cutblocks and adjacent non-treated controls in northern Alberta. Size of symbol increases with species richness. Ordination stress=0.18. Vectors shown are species having significant indicator relationships with the different treatment groups ($p \leq 0.05$). Species vectors shown include *Betula papyrifera* (BW), *Calamagrostis canadensis* (CALCAN), *Carex* sp. (CAREXSP), *Epilobium glandulosum* (EPIGLA), *Equisetum arvense* (EQUARV), *Equisetum sylvaticum* (EQUSYL), *Picea glauca* (SW), *Populus balsamifera* (PB), *Populus tremuloides* (AW), *Rosa acicularis* (ROSACI), *Rubus idaeus* (RUBIDA), *Salix* sp. and *Viburnum edule* (VIBEDU).

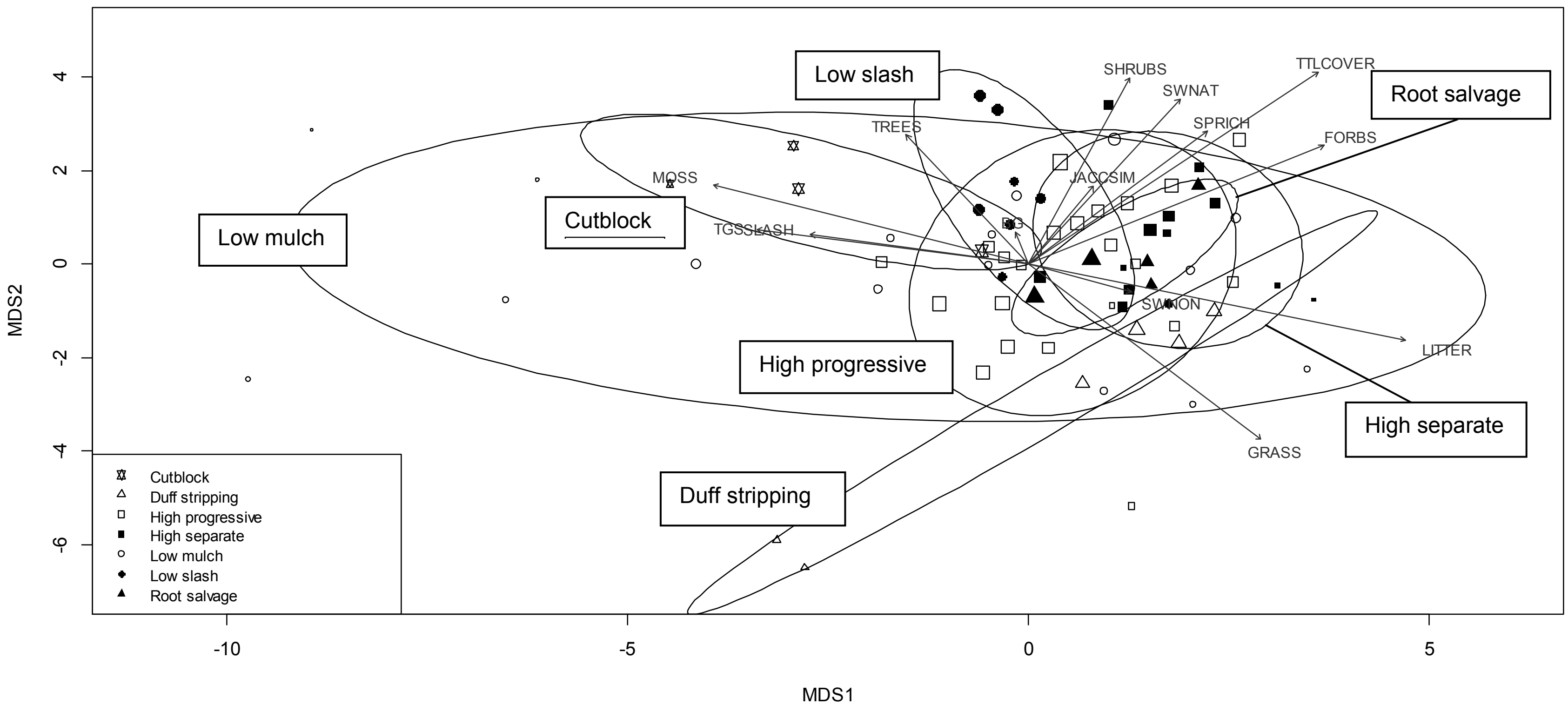

Figure 2.5. NMDS ordination plot depicting summary plant community characteristics in study sites (except deep and shallow mulch) contrasting low through high soil disturbance treatments from well sites and cutblocks. Factors include percent cover of litter, slash, moss, bare ground, total cover, grass, forb, shrub, and tree cover, ratio of tree to grass and shrub cover (TGS), Shannon Weiner (SW) native and non-native diversity and Jaccard similarity index (JACCSIM). Size of symbol increases with species richness. Ordination stress=0.18.

CHAPTER III: LONG TERM EFFECTS OF WELL SITE DISTURBANCE ON PLANTED SPRUCE AND REGENERATING ASPEN

1. INTRODUCTION

Factors that contribute to poor reforestation on upland boreal oil sands exploration sites in northeastern Alberta, Canada, may be mitigated during construction and/or reclamation phases of development. Northeastern Alberta is extensively managed for timber production and oil sands exploration sites often occur within a forest management agreement area. Thus, there is a desire for reclamation outcomes to return the land to productive harvest rotation. Prior to the 1990s, post-harvest operations focussed on monocultural re-establishment of *Picea glauca* (Moench) Voss (white spruce) to meet projected market demand for timber.

White spruce is commonly planted post disturbance as its natural regeneration patterns are temporally erratic. The foremost reproductive strategy of white spruce is wind dispersed seed that falls from autumn through winter, with abundant seed production only in mast years. Seeds can germinate in newly disturbed areas on exposed mineral soil, humus and woody substrates (Peters et al 2006, Purdy et al 2002, Zasada and Gregory 1969, Eis 1967). Under developed forest canopies, seedlings will establish on woody debris in various stages of decay (Gärtner et al 2011, Beach and Halpern 2001, Christy and Mack 1984, Day 1972) and among feathermosses (LaRoi and Stringer 1976). On open sites, most naturally regenerating seedlings perish due to water stress (Abrahamson 2015). White spruce growth and survival in Alberta is commonly impacted by frost damage, snow press, browsing from wild ungulates and small mammals, excessive moisture and competing vegetation including *Calamagrostis canadensis* (Michx) Beauv (bluejoint), a common herb in the boreal forest, and *Populus tremuloides* Michx (trembling aspen) (Abrahamson 2015, Cole et al 2003, Frey et al 2003a, Lieffers et al 1993).

Managing for mixed trembling aspen and white spruce stands is increasingly of key interest in Alberta (Pitt et al 2010). Growing awareness of biodiversity and social values associated with the boreal forest, and an increased market demand for aspen have shifted forestry practices toward mixedwood management, which by the mid 1990s became the highest research priority in Alberta forests (Grover and Fast 2007, MacDonald 1995, Forest Research Advisory Council of Canada 1994, Boyle 1992, Suffling et al 1988). Trembling aspen can reproduce by seed on mineral substrates, but requires continuous moisture for seedlings to establish (USDA 2003). Aspen is primarily a clonal species that vigorously resprouts following harvest and natural disturbance (eg fire). This is attributable to the removal of above ground biomass and hormonal triggering of sucker growth from roots, which can produce very high densities of robust clones with warm soil conditions on moderately well to well drained sites (Frey et al 2003a, 2003b). Defoliating insects have had severe impacts on trembling aspen in the western boreal, especially in conjunction with drought (Cooke and Roland 2007). Regeneration densities are greatly reduced by root severing and fragmentation (Frey et al 2003a). Aspen are prone to suppression by bluejoint, partly due to competition, and also to soil cooling associated with the thick recalcitrant litter arising from this species (Landhäusser and Lieffers 1998).

Other regional pioneer tree species include *Populus balsamifera* L (balsam poplar) and *Betula papyrifera* Marshall (paper birch). Birch sheds abundant wind dispersed seed in fall through winter (Uchytil 1991). Seeds germinate the following spring on exposed mineral or mixed organo mineral soils and require continuous moisture for seedling establishment. Paper birch resprouts from root collars after stem removal, often forming pure stands or codominates with aspen. It has been used for long term stabilization of severely disturbed Alberta landscapes. Balsam poplar establishes post disturbance on hygric to mesic, moderate to nutrient rich sites through seeding, suckering and sprouting from stem and branch pieces (Harris 1990). Prolific seed dispersal occurs in early spring before bud flush and seeds germinate on moist exposed mineral soil. Partially buried branches form new trees, sprouting occurs after stem removal, and suckering is common after soil disturbance; suckers of poplar are more vigorous than of aspen.

Little is known about long term effects of oil sands exploration well site disturbances on survival and growth of planted spruce, naturally regenerating trees and associated physical and chemical properties of boreal forest soils. Exploration well operations are small but numerous, creating many disturbances across a large area with spatially and seasonally limited access. Thus reclamation targets must be clear and techniques efficient during construction and reclamation development phases. Re-entering sites to amend a reclamation project generates more disturbance and is financially undesirable. Soil management in construction, storage and reclamation phases directly impact propagule survival, and therefore vegetation recovery.

2. RESEARCH OBJECTIVES

This research was conducted to identify factors that contribute to successful reforestation of upland well sites in Alberta boreal forest to further develop best management practices for construction and reclamation. Success is defined as identifying factors that facilitate successional development convergent with the surrounding forest, including factors that promote regeneration and development of aspen, and factors that promote survival and growth of planted spruce. A-priori use of well site treatments allowed for direct comparison of conventional methods with alternative construction and revegetation methods thought to reduce impacts on existing vegetation, remaining plant propagules and associated soil. The following specific objectives were addressed.

- To assess how similar tree establishment was on nine to ten year old well sites with different treatments to forests recovering from post harvest disturbance (cutblocks). To determine whether disturbances changed density patterns of recovering forest and to identify treatments that caused more or less change to early tree establishment than others. Factors assessed included well site construction and reclamation methods and site conditions.
- To assess low disturbance (iced-in with no soil excavation), high disturbance (conventional soil stripping), duff stripping and root salvage soil treatments. Low disturbance, duff stripping and root salvage sites were compared with conventional soil stripping sites to assess effect of excavation method on regenerating aspen and soil chemical and physical properties.
- To assess effects of soil disturbance and storage methods on planted spruce, regenerating aspen and soil chemical and physical properties. Stripped soil components (woody debris, surface organic layer, upper mineral soils) were piled in a single progressive pile (one on top the other) or in separated piles.
- To assess effects of woody debris type and distribution used in reclamation on planted spruce and regenerating aspen. On conventional sites, coarse woody materials were evenly spread across the site, or spread on one half and windrowed on the other. On low disturbance sites, woody materials were spread as whole slash on half the site and windrowed on the other, or mulched and spread across the whole site. Deep versus shallow mulching effects were also assessed.
- To assess effects of initial tree planting on regenerating tree densities and aspen growth (all but root salvage sites were planted with 150 to 200 trees on a random half of the site).

3. METHODS

3.1. Research Site Descriptions

Research sites were in boreal forest near Anzac, Alberta (Figure 3.1) in Central Mixedwood Natural Subregion (Global forest Watch Canada 2005). Sites span 40 km from Townships 82 to 86, between Ranges 6 and 8, west of the 4th Meridian. Four cutblocks, harvested and planted with white spruce in 2004 within Township 85, Range 6 were sampled. The region is characterized by gently rolling to hummocky moraine receding to lacustrine flats underlain by Cretaceous shales (Natural Regions Committee 2006, Rowe 1972). Sites were mid to late seral forest prior to current disturbances, with mesic to sub-mesic aspen or aspen white spruce mixes in variable proportions on Gray Luvisolic soils of varying texture. Ecotypic understory species ranged from *Viburnum edule* (Michx) Raf (low bush cranberry), *Rosa acicularis* Lindl (prickly wild rose), *Alnus viridis* (Chaix) DC (green alder) or *Cornus sericea* L (red osier dogwood), to *Ledum groenlandicum* Oeder (Labrador tea), Ericaceous shrubs, and feather mosses.

3.2. Experimental Design, Treatments And Plot Establishment

Thirty-three well sites selected for research were developed for oil sands exploration between 2004 and 2006 and reclaimed during the winter months using different soil handling and woody debris management methods (Table 3.1). Each treatment group consisted of two to three well sites, with each site combining soil and woody debris management treatments. Well sites were mostly 70 x 70 m in size; one root salvage site was 70 x 90 m and two sites were 70 x 100 m. Four plots were established in each treatment at each site. Plots established in 2004 were 10 x 10 m; those established in 2005 and 2006 were 12 x 12 m. The exception was mulch depth treatments, which had three 3 x 3 m plots in each treatment at each site (Figure 2.2).

Except for six root salvage sites, whose excavation method was designed to examine natural tree regeneration, all sites were planted in early summer following reclamation with 150 to 200 trees on a randomly selected half of the site, for planted and non-planted treatments (Figure 3.2). Trees were planted at 2 m grid spacing, for a planting density of 3,300 trees per hectare. Twelve individuals of each species were planted in each plot (three of each species in deep and shallow mulch treatment plots). In 2004, alternating rows of trembling aspen, balsam poplar and white spruce, were planted. Sites reclaimed in 2005 and 2006 were planted with the same species plus paper birch.

Thirteen sites were constructed with a low disturbance (iced-in) method. Little soil disturbance occurred at these locations. Mulch, snow and ice were used to build a level construction platform. On eight of these, non-merchantable vegetation was mulched and spread at variable depths according to standard management methods during reclamation. At three sites, mulch was spread to depths of ≤ 5 cm and ≥10 cm in alternating 10 m wide strips (hereafter shallow and deep mulch treatments, respectively). On the remaining two low disturbance sites, residual woody debris was spread as whole slash on half the site and windrowed on the other.

Eleven study sites were constructed and reclaimed conventionally. On five sites, salvaged slash was evenly spread across the site. On six sites half of the site was windrowed and on the other half slash spread evenly at reclamation. During construction, soils were stripped by a dozer in two passes. The first pass removed LFH (organic) layer and the second underlying mineral Ae horizon, usually with some of B horizon when the Ae horizon was < 15 cm depth. Stripped soils were stored at the edge of the site, usually for three to four weeks, and then replaced.

Three sites with single (progressive) soil piles were selected to compare to three sites with separated piles. Site space limitations occasionally required one progressive pile, with slash on the bottom, then LFH, then surface soil and possibly B horizon. At the other three sites, soils were piled separately with LFH and A horizon in one pile, and B horizon in another, with the latter placed first during reclamation. Piling soils separately may be beneficial by reducing mixing of soil layers, thereby limiting alteration of physical and chemical properties of excavated soils, and preventing deep burial of seeds and propagules important for revegetation (Osko and Glasgow 2010). Attempts were made to replace all soils according to their originating depth, but it is likely more mixing of layers occurred in soils that were progressively piled.

Root salvage treatments were applied at the remaining six well sites, which were compared to five conventionally constructed sites established using progressive soil piles. Conventional two-pass stripping is often performed using soil colour as an indicator of stripping depth. Aspen roots are mostly located where a soil colour change occurs at the interface of LFH and Ae horizons (Osko and Glasgow 2010). The first pass in the root salvage technique excavated at a greater depth to prevent root damage by equipment. During storage, aspen roots were bound within larger soil aggregates than with conventional stripping. A second pass including the lower Ae and some B horizon was performed where necessary to level the lease prior to construction. Soils from the second pass were piled separately.

Three study sites were constructed with a duff stripping method, removing only the LFH layer and occasionally a small amount of mineral A horizon. Strippings were stored in a single pile together with residual slash. These sites were compared to low disturbance sites with mulch, and conventional sites with spread slash to determine if duff stripping provided a lesser disturbance than the two-pass soil stripping.

3.3. Planted Spruce Measurement

In 2014, trees planted in 2004 and 2005 were assessed May 22 to 29 on sites in Townships 84 and 86, and June 10 to 16 on sites in Townships 82 and 83. In 2015, trees planted in 2006 were assessed May 25 to June 29 in Townships 82, 83 and 84. Planted spruce trees in plots were first located. Root crown diameter and diameter at breast height were measured using calipers (trees up to 20 cm diameter) or root crown diameter and diameter at breast height using a diameter tape (trees > 20 cm diameter). Heights were measured with a tape (trees up to 5 m) or Suunto clinometer (trees > 5 m). Dead, missing and damaged trees were recorded.

3.4. Regenerating Tree Density Assessment

In 2014, natural revegetation was assessed for sites reclaimed in 2004 and 2005. Sites in Townships 84 to 86 were assessed July 14 to 28; sites in Township 82 and cutblocks (Township 85) were assessed August 4 to 13. In 2015, sites reclaimed in 2006 were assessed in Township 84 July 27 to August 18, and in Townships 82 and 83 August 13 to 16.

At each site, five 1 x 1 m quadrats were randomly located in each plot for a total of 20 quadrats per treatment. For deep and shallow mulch treatments, four 1 x 1 m quadrats were randomly located in each plot for a total of 12 quadrats per treatment type. For sites with a single woody material treatment (mulched or spread), transects were established from one corner of a reference plot to its opposite corner, approximating a north westerly direction. For sites with woody material spread on one half and windrowed on the other, transects radiated from the centre of each site as maintaining orientation within dense growth of some sites was difficult. Transects thus crossed both shaded and lit portions of each plot (if situated at site edge), and crossed windrows where present. Ground cover was assessed for bare soil, litter, woody debris, moss and lichen. All naturally regenerating trees in quadrats were counted, and average height and diameter at breast height were recorded as class variables (Table 3.3).

Cutblocks were similarly sampled. Transects were established 20 m from cutblock edges. At each cutblock, one transect was in a northerly direction, then easterly, southerly and westerly. Five 1 x 1 m quadrats were located 15 to 20 m apart along each transect using stratified random sampling. Areas disturbed since harvest (recreational vehicle use) and those clearly a lowland or riparian ecotype were avoided. A total of 20 quadrats were assessed per cutblock.

3.5. Soil Sampling And Laboratory Analyses

In 2015, soil was sampled from the six root salvage sites. Six subsamples were obtained both on and off site at random locations at least 20 m apart. For each core, the organic layer was removed, and the mineral layer exposed. Samples were taken with a 7.5 cm diameter x 7.5 cm long Uhland corer at 0 to 15 and 15 to 30 cm depths. Following extraction, samples were stored in coolers until transported to a temporary laboratory for preliminary processing, where they were weighed fresh and then air dried for up to four weeks. Once dry, samples were weighed to determine water content. Soils were then sieved, rocks and roots removed and final volume determined to calculate bulk density (Blake 1965). The six samples from each site were amalgamated within each depth class, and the six samples from each forest control also amalgamated within each depth class, before sending to the laboratory for chemical analysis.

Soil at all other sites was sampled the summer following reclamation. Three soil samples were taken at 6 and 30 cm depths from each of four quadrants of each site, and an equal number from an offsite reference area. Bulk density for 2004 sites was assessed using a gamma ray transmission probe (Campbell and Henshall 1991). This method was abandoned in subsequent years due to difficulty gaining permission to use the technology in the energy industry. Samples from each onsite treatment community and each forest control were then amalgamated within each depth class before sending to the laboratory. Soils in cutblocks were not sampled.

Physical and chemical analyses for 2004 to 2006 samples were conducted by Bodycote testing group; those from 2015 were analyzed at ALS Laboratories. Available nitrate was determined by calcium chloride solution and colourimetry (Laverty and Bollo-Kamara 1988); phosphorus and potassium by modified Kelowna solution and colourimetry (Ashworth and Mrazek 1995); available sulfur by calcium chloride solution and inductively coupled plasma atomic emission spectroscopy (Laverty and Bollo-Kamara 1988); total carbon and total nitrogen by dry combustion (Nelson and Sommers 1996); inorganic carbon by acid digestion (Loeppert and Suarez 1996); pH and electrical conductivity in saturated paste (2:1 soil to water) with a meter (Miller and Curtin 2008); and particle size by hydrometer method (Kroetsch and Wang 2008).

3.6. Statistical Analyses

Analyses were performed using R 3.2.5 software (R Core Team 2016). An alpha value of 0.10 was used due to small sample size. Inspections of similarity of regenerating tree densities within treatment communities to tree development after harvest and between treatment comparisons of native tree reestablishment were conducted. A second set of data pertaining to performance of planted spruce was compared between treatments only. Statistical methods for analysis of this dataset included MANOVA, contrasts and ANOVA of linear mixed effects with REML. Where treatment interactions were detected, LSD tests were performed to identify differences between means, with a Bonferroni correction to control the family wise error rate. All data were checked for normality and homoscedasticity prior to analysis. Survival for planted spruce followed a Poisson distribution and was arcsine square root transformed to improve normality. Exponential transformations of aspen growth parameters were often implemented as datasets were not always balanced due to poor regeneration in some treatments. Where data could not be transformed to meet assumptions of parametric analysis, non-parametric methods were used, including Wilcoxon and Levene tests, or multiple response permutational procedure (MRPP). Means and standard errors shown in tables are untransformed. Soil parameters were analyzed using ANOVA and orthogonal contrasts. Electrical conductivity was log transformed.

All study sites were grouped by soil disturbance and compared to cutblocks. Low disturbance sites with mulch and spread slash were grouped separately. For simplicity, deep and shallow mulch sites were not included. Cutblock tree densities and regenerating aspen performance were compared to treatment communities using ANOVA to assess differences in tree regeneration characteristics and make inferences regarding degree of alteration due to type of disturbance. Tree densities and regenerating aspen performance were compared among pre-determined treatment groups. Planted spruce performance and soil metrics were compared among pre-determined treatment groups to determine relative effects of treatments.

Deep and shallow mulch treatments were analyzed as a nested split plot design; high versus low disturbance treatment group and duff stripping sites were analyzed with a split plot design. Data of groups with direct comparisons of deep and shallow mulch, high and low disturbance, and high and low disturbances versus duff stripping, were analyzed using two-way ANOVA.

Due to the experimental design, root salvage sites had only one observation (community) for comparison, and two-pass stripping sites had two observations per site as all but root salvage sites had planted and non-planted treatments. Root salvage sites were therefore compared with only the unplanted portion of high disturbance sites with one-way ANOVA. Low disturbance sites with spread and windrowed slash were in a split plot design, and compared to low disturbance sites with mulch using contrasts. Where soil piling methods were compared, sites were analyzed in a split-plot design and compared with two-way ANOVA.

When this study was initiated, performance of four planted tree species was of interest for their potential to establish on oil sands exploration sites, including their influence on site recovery, and what each species may reveal about disturbance impacts. At this point in the reclamation timeline only planted spruce could be reliably observed. Planted aspen performed poorly, often looked stunted, and many had sun scorched bark, particularly on mulch sites. Heavy

Malacosoma disstria Hbn (forest tent caterpillar) damage was observed within a few years of planting. Over time many aspen trees were near dead with the occasional new sucker emerging in subsequent years. Planted balsam poplar performed quite well on many sites, and often achieved heights > 6 m, but tracking of planted trees on many sites was confounded by establishment of native poplars, which were similarly robust and therefore indistinguishable from those planted. Planted birch performed well but approximately one third were heavily browsed and stunted, leaving some with a shrub like appearance. Many had broken tops, usually at 1.2 to 1.6 m height. Only white spruce could reliably be recognized as planted origin with growth and survival measurable against site conditions without obvious confounding factors.

Spruce performance is of concern as its presence is a necessary element in expeditious recovery of well sites to mixedwood stands. The other planted trees are typically pioneer species of the region that can rapidly colonize post disturbance. They were dominant naturally regenerating species and preferentially regenerated in response to select treatments.

All sites had one common disturbance characteristic; vegetation was removed. Therefore, cutblocks harvested in the same time frame as well site reclamation provided a good reference for physical characteristics of natural canopy recovery in the absence of soil disturbance.

Density and growth of eight native tree species were recorded across treatments. Proportions of naturally regenerating tree densities and total density (stems m^{-2}) in each soil disturbance treatment and cutblock plot are shown in Figure B.1 (Appendix B). Occurrences of four conifers other than white spruce were controlled by location differences and proximity to local seed sources. These were *Picea mariana* (Mill) Britton, Sterns and Poggenb (black spruce), *Pinus banksiana* Lamb (jack pine), *Larix laricina* (Du Roi) K Koch (tamarack), and *Abies balsamea* (L) Mill (balsam fir). These species did not contribute significantly to forest re-establishment relative to any treatment, but did take up ecological canopy space. Therefore their numbers remain in comparison to total tree density by treatment (Tables 3.3 and 3.4, Figure 3.3), but their specific densities are not compared between treatments. Relative densities were compared of dominant naturally regenerating species, and total tree densities between all soil treatments (Table 3.3).

4. RESULTS

Cutblocks had highest mean total density at 52,000 trees per ha, but were not different from low disturbance and root salvage treatments, at 26,000 to 32,000. Duff stripping resulted in lowest total tree density (8,800 trees per ha). Total density was most strongly correlated with birch density, then aspen. Densities of naturally regenerating spruce did not differ with soil treatment, but poplar establishment was high on root salvage sites (20,000 trees per ha) (Table 3.3). Specific comparisons of naturally regenerating tree densities between soil disturbance treatments and wood treatment groupings are provided in Table 3.4.

A gradient of disturbance was observed through regenerating aspen densities as it is the most sensitive of pioneering trees in this study to the range of disturbances that oil sands exploration creates. Aspen regeneration was highest in cutblocks (12,000 trees per ha), and lower where soils had been excavated, with as little as 500 trees per ha (Table 3.3). Aspen DBH did not differ between soil treatments, but aspen height was greater in cutblocks and lower on root salvage sites. When all soil disturbance groups were compared, no differences were found in survival and growth of planted spruce (Table 3.3).

4.1. Effect Of Soil Disturbance

Spruce survival was lower in low disturbance ($p = 0.088$). Of surviving planted spruce, height and DBH did not differ between high and low disturbance treatments, although this analysis may have been constrained by a low sample size (Figure 3.5, Table 3.5). Low disturbance methods resulted in greater aspen density ($p = 0.007$) with more than three times that in high disturbance treatment (5,700 compared to 1,600 trees per ha). Aspen DBH and height were greater in the low disturbance treatment ($p = 0.025$ and 0.030, respectively) (Figure 3.5 and Table 3.5).

When high and low disturbance treatments were individually compared to duff stripping, no differences were found in aspen growth, although aspen density was higher in the low disturbance treatment than duff stripping ($p = 0.094$, Table 3.6). Height and survival of planted spruce did not differ between these treatments although spruce DBH was greater on high disturbance sites than duff stripping sites ($p = 0.063$) (Table 3.6). Of the three treatments, duff stripping led to lowest total tree density ($p = 0.003$), with smaller populations of regenerating spruce and birch ($p = 0.014$ and 0.003, respectively) (Table 3.4).

Carbon and nitrogen were locally greater at high disturbance sites (Osko and Glasgow 2010). While clay was more abundant where the low disturbance method was used, both high and low disturbance sites were constructed over better drained soils than duff stripping sites (Osko and Glasgow 2010) (Table 3.7). Duff stripping resulted in increased available potassium ($p = 0.044$). Organic carbon and nitrogen content were higher in the high disturbance and duff stripping treatments than forest controls (Osko and Glasgow 2010) (Table 3.7), but no differences were found between low disturbance treatment and controls (Osko and Glasgow 2010).

In a paired comparison of cutblocks to low disturbance sites with mulch, aspen density was lower and DBH higher in the low disturbance treatment ($p = 0.011$ and 0.009, respectively) (Table 3.8). Low disturbance sites had more poplar, but lower total density than cutblocks ($p = <0.001$ and 0.033, respectively) (Table 3.4). Soils did not differ between low disturbance sites and forest controls, and bulk densities were slightly higher onsite.

Aspen density or growth did not differ between high disturbance and root salvage treatments (Table 3.8). There were no differences in total tree density, although birch density was greater and poplar density lower with high disturbance ($p = 0.048$ and <0.001, respectively) (Table 3.4). Soils were loamier where root salvage was used, and high disturbance sites had higher C:N ratio ($p = 0.008$) (Table 3.8). Electrical conductivity and pH were greater on root salvage sites at 6 cm depth ($p = 0.002$ and 0.043, respectively). These differences were also observed between the root salvage treatment and forest controls ($p = 0.027$ and <0.001, respectively) (Table 3.8).

4.2. Effect Of Soil Pile Management

Total tree, birch and aspen density were lower on soils that had been separately rather than progressively piled ($p = 0.019$, 0.001, and 0.002, respectively) (Table 3.4). No differences were found in growth of regenerating aspen, or growth and survival of planted spruce (Table 3.9).

Treatment locations differed in some soil properties. Available potassium, clay content, available nitrogen and electrical conductivity were greater with progressive soil piling ($p = 0.024$, 0.043, 0.077 and 0.071, respectively) (Table 3.10). Available phosphorus was higher onsite than in forest controls where soils were progressively piled ($p = 0.001$). Soil pH increased relative to controls for both piling treatments, to a greater degree with progressive soil piling ($p = 0.031$).

C:N ratio did not differ between forest controls but was greater in progressive than separate soil piling ($p = 0.019$) (Table 3.10). Total soil organic carbon was greater under piling treatments than forest controls, but of greater magnitude in progressive than separately piled soils (57.6 % and 22.2 %, respectively). Progressive soil pile plots had slightly greater nitrogen than forest controls but there was 2.5 fold more in separately piled soils than forest controls (Table 3.10).

4.3. Effect Of Woody Debris Treatment

Between mulch and whole slash treatments in low disturbance sites, no differences in planted spruce or regenerating aspen performance were found (Table 3.11). Aspen density in whole slash treatments was more similar to that in cutblocks (Table 3.3). When soil disturbance treatments were compared, all three wood treatments resulted in similar birch and total tree densities to cutblocks (Table 3.3), but when specifically compared to one another, mulch application resulted in fewer birch than whole slash treatments ($p = 0.002$) (Table 3.4). The mulch treatment had greater poplar and spruce densities than whole slash treatments ($p = 0.003$ and 0.031, respectively) (Table 3.4).

The area where mulch was applied had sandier soils and higher bulk density ($p = 0.035$ and 0.031, respectively) (Table 3.12). Soil water content and pH were higher with mulch ($p = 0.068$, and 0.004, respectively). Electrical conductivity was lower in mulch than whole slash treatments ($p = 0.004$), which tended to have lower available potassium and sulfur ($p = 0.074$ and 0.005, respectively). Conversely, total soil organic carbon was greater in windrowed slash and lower in mulch at the 30 cm depth ($p = 0.023$) (Table 3.12). Total organic carbon did not differ between forest controls of mulch and whole slash treatments.

No differences in soil physical and chemical properties were found between contrasting mulch depth treatments (shallow versus deep), and depth of mulch did not influence planted spruce performance. There was considerable variation in response metrics due to site, and differences in planted spruce performance may have become apparent with a larger sample size of well sites (Table 3.13). Aspen density and height were lower ($p = 0.077$ and 0.061, respectively) and poplar density greater ($p = 0.027$) (Table 3.13) in deep mulch than shallow mulch areas.

In the high disturbance treatment, planted spruce responded differently to contrasting wood treatments in progressive and separate soil pile treatments. Spruce height and DBH ($p = 0.061$ and 0.031, respectively) and aspen density ($p = 0.067$) were lower in the spread slash treatment where soils had been piled separately (Figure 3.6 and Table 3.9). Comparison of soils from spread and windrowed slash treatments associated with sites where soils had been piled separately had greater potassium content in the windrow treatment ($p = 0.056$) (Table 3.10). Ground cover variables from the year of tree planting were examined. Where spread evenly across the site, there was greater slash cover and less moss cover ($p = 0.025$ and 0.005, respectively) (Table 3.10).

4.4. Effect Of Tree Planting Treatment

Aspen in high and low disturbance treatments appeared to respond differently to planting. Aspen density was greater in the planted low disturbance treatment ($p = 0.007$) (Table 3.5).

Similarly, aspen density was higher in the planted low disturbance treatment than duff stripping ($p = 0.026$) (Table 3.6). Poplar and total tree density were greater in the planted treatment in deep mulch treatments ($p = 0.016$ and 0.059, respectively) (Table 3.13).

5. DISCUSSION

Aspen stems were expected to provide a greater proportion of total density on cutblocks and oil sands exploration sites constructed with lower soil disturbance methods. Higher birch densities on cutblocks may be due to abundant local birch seed. Lesser aspen density in low disturbance whole slash treatments is likely due to the size of area harvested prior to construction. Cutblocks are much larger than oil sands exploration sites, and much more aspen biomass was removed. Clear cutting often results in aspen densities from 50,000 to 100,000 trees per ha (Frey et al 2003a), but partial cutting, comparable to oil sands exploration site disturbance, can inhibit sprouting due to residual apical dominance (and therefore hormonal control) of nearby trees and shade they produce (Frey et al 2003a). Aspen root suckering in response to partial cutting has been much less than suckering after clear cut harvest (Frey et al 2003b).

Many planted aspen were affected by defoliation from forest tent caterpillars, and appeared desiccated. Naturally regenerating aspen were also likely affected. Aspen populations throughout North America have been increasingly stressed by climate change and drought (Michaelian et al 2011). Hogg et al (2002) found populations in northern Alberta were increasingly impacted by insect and climate stressors. Drought was widespread across Alberta in 2009 and 2010, which may have impacted regenerating aspen. Young aspen primarily regenerate through root suckering, and each sucker is a clone, part of a larger interconnected population. Clones benefit from connectedness in the stand, which shares resources and increases resistance to disease and insects. These benefits become limited with stand stress.

Young aspen in this study faced competition from birch, poplar, dense grasses and shrubs in some treatments. Birch produce abundant seed and can rapidly colonize post disturbance (Uchytil 1991). Although they require consistent soil water for the first month post germination, they have evolved a tolerance to broad variation in moisture availability (Uchytil 1991). Poplar likely established through root suckering on cutblocks and low disturbance sites, which is stimulated by overstory removal (Harris 1990). Poplar suckers are more vigorous than aspen suckers, and balsam poplar enhances its potential for dominance with quick growth through the juvenile stage (Harris 1990). Thus, already impacted by climatic stress and insect damage, under increasing competition aspen may have thinned out, allowing birch to dominate.

The similar birch densities between cutblocks and low disturbance treatments and similar aspen density between cutblocks and low disturbance sites with whole slash, while mulched sites had less aspen than cutblocks suggests mulch was more detrimental to aspen than direct vegetation disturbance during oil sands exploration. Although aspen density can be significantly reduced by soil compaction (Berger et al 2004, Stone and Eliof 1998, Shepperd 1993), no difference was found in bulk density between mulch treatments and forest controls. Lower aspen densities in the mulched low disturbance treatment were likely due to the mulch left on site, and density was further reduced with increasing mulch depth. Mulch spread at depths > 4 cm can impede aspen regrowth. It imposes a physical barrier and slows regeneration by insulating soil, and maintaining cool temperatures further into the growing season (Vinge and Pyper 2012, Landhäusser et al 2007). This can delay emergence which puts suckers at a competitive disadvantage (Frey et al 2003a). Although results imply aspen density improved by planting on low disturbance sites, on two of five sites tree planting was applied where mulch was shallower. Higher density of aspen in the planted low disturbance treatment was most likely in response to warmer soil temperatures and a reduced physical barrier in the shallow than deep mulch.

All soil treatments that involved soil excavation resulted in significantly lower aspen density than cutblocks. In northern Alberta, suckers typically emerge from intact aspen root systems at approximately 8 cm below soil surface, and root fragments can successfully sucker and emerge when placed as deep as 20 cm (Landhäusser et al 2015). Many roots tend to get sorted to the surface among soil and other organic debris, which being denser, tend to settle lower when transferred by large equipment; roots are thus replaced above the soil surface (Landhäusser et al 2015). Exposed roots are prone to lethal water loss (Weber 2011).

Aspen roots were likely damaged in other ways by high disturbance. Kabzems and Haeussler (2005) found scraping and severing of aspen roots by excavator buckets during conventional soil stripping. Further damage would have been incurred during soil replacement. While some wounding can stimulate suckering (Fraser et al 2004), excess damage compromises root viability. Individual aspen trees regenerating from fragmented roots do not benefit from clonal resource sharing and storage capacity, which otherwise facilitates tree growth and resilience over time (Rhodes et al 2016). Much of the carbohydrates produced by new suckers from root fragments are dedicated to rebuilding below ground roots (Frey et al 2003a). Some boreal species benefit from root fragmentation (bluejoint) produced by soil excavation, and can rapidly colonize disturbed soils. Aspen are prone to suppression by bluejoint partly due to competition, but also to soil cooling due to thick recalcitrant litter (Landhäusser and Lieffers 1998).

Aspen density in high disturbance sites was further reduced by separate than progressive soil piling. Frey et al (2003b) found soil mixing and subsequent damage to propagules in combination with reduced available nitrogen relative to controls negatively impacted vegetation reestablishment. Conversely, in our study, fragmented aspen roots responded better in soils with reduced available nitrogen. Aspen regeneration in soil piling treatments may have been influenced by relative abundances of available phosphorus and potassium. Young aspen can allocate greater resources to root systems with decreasing nitrogen, phosphorus and potassium fertilizer applications (Coleman et al 1998). In absence of fertilizer, aspen growth has been positively correlated with available potassium in severely disturbed soils (Pinno et al 2011).

Seeds and propagules were likely at higher risk of desiccation in separate soil piles. Oil sands exploration sites and spoil piles have a typical life span of a few winter months. Piled soils no longer thermally protected by layers of snow and organic material, are exposed to the atmosphere and lower temperatures, and thereby lose vegetation propagules to desiccation. Desiccation of aspen roots due to exposure was observed by Landhäusser et al (2015) when root fragments were located close to the disturbed soil surface, or covered by only loosened (porous) soil material. This effect during storage was likely greater in separate piles, where a larger surface area of soil, and therefore root fragments, would have been exposed.

Windrowing rather than evenly spreading slash appeared to mitigate some impacts of separate soil piling, and improve aspen regeneration. This may be due to warming of soil between windrows not covered by slash, thereby stimulating tree regrowth (Frey et al 2003a). Cool soil temperatures can suppress or delay aspen emergence, putting suckers at a competitive disadvantage as a result of slash retention. More available potassium in the windrow treatment may be evidence of higher microbial activity and microbial recovery in response to warmer soil which would have a positive effect on aspen growth. Greater moss was observed in the windrow than spread slash treatment. Moss promotes colonization of species that reproduce vegatatively by reducing available germination space (Hart and Chen 2006).

The lower birch and total tree densities with high disturbance than cutblocks may be associated with lower soil pH (4.5 to 5.3) in the low disturbance treatment, as it increased with high disturbance, relative to forest controls. Although birch seedlings can perish on soils with pH < 5.0 (Uchytil 1991), this study supports Beckingham (1993) that paper birch prefers soils with pH < 5.3. In excavation treatments soil pH was 5.4 with high disturbance and 6.7 with root salvage.

Poplars typically have high nutrient requirements (Harris 1990). Higher poplar density on excavated sites may partly be in response to nutrient release that occurs with soil mixing, in combination with rapid early tree growth and reduced competition from other trees (aspen). Balsam poplar has multiple successful regeneration methods. It is likely that there is fairly even distribution of both poplar seedlings and regenerating poplar from root and stem fragments.

Root salvage was intended to improve aspen density by retaining larger pieces of intact aspen roots and provide better protection of roots during storage in large soil aggregates. However, aspen density on these sites was not different from other high disturbance treatments. It is likely that aspen regeneration on these sites was impeded by poplar regeneration. With rapid early growth, intact poplar root systems in the loamy, nutrient rich soils where root salvage was implemented would have had a competitive advantage over regenerating aspen.

The duff stripping treatment was similarly intended to improve aspen tree density. Although aspen densities on these sites did not differ from low disturbance sites with mulch, total tree, birch and spruce densities were all lower than in high and low disturbance treatments. Qi and Scarratt (1998) found most tree seeds in boreal soils were located in the lower layer of organic (LFH) material. Both birch and spruce shed their seed in fall through winter months for germination the following spring (Abrahamson 2015, Uchytil 1991). As with all soil stripping procedures in this study, these would have been removed as part of duff stripping, but unlike other soil stripping procedures, were not buried, but more exposed to environmental conditions.

Seeds of trees (and shrubs) in general are more prone to desiccation than other vegetation groups (Gold and Hay 2014), and may be even more susceptible to atmospheric conditions stored in relatively porous duff material, not protected by a denser soil matrix. In a greenhouse experiment, seedling establishment of germinated seeds in disturbed or loosened organic material was lessened due to poor water retention (Qi and Scarratt 1998). Therefore, seeds that did survive storage may have had reduced establishment success.

Similarly, low densities of birch and spruce with separate soil piling put propagules and seeds at high risk of exposure and desiccation. New seeds from birch and spruce would not arrive on sites until after the first season of regrowth. Perhaps due to lower slash cover and greater moss cover in the windrowed slash treatment, spruce establishment tended to increase. While moss cover deters germination of many species (Hart and Chen 2006), white spruce commonly establishes on moss (LaRoi and Stringer 1976).

In the absence of exposed mineral or humus surfaces, conifers preferentially select sound and decayed woody debris as a germination substrate in recently disturbed forests and under established canopies (Beach and Halpern 2001). It is unlikely, however, that mulch was preferentially selected over spread and windrowed slash, which would have had exposed mineral soil available. Higher spruce densities in the mulch treatment are likely due to spruce branches and seeds incorporated into mulch, thereby providing a seed source for trees.

Overall, the highly variable planted spruce growth between treatments and the differences observed were mostly not significant, and may have been constrained by low sample sizes. Higher mean growth for spruce in the high disturbance treatment may have been influenced by greater local access to soil carbon and nitrogen, coupled with soil disturbance effects. Mixing LFH and mineral horizons can result in nitrogen mineralization, as observed after forest soil disturbance (Vitousek et al 1979, Vitousek and Melillo 1979) and mechanical site preparation (Gradowski et al 2008, Munson et al 1993). Planted spruce may have benefitted from mixing soil layers, warming exposed mineral soil, and resulting nutrient release. Mechanical site preparation is a preferred treatment for white spruce in the western Canada boreal region (Boateng et al 2006, Archibold et al 2000). This effect is short term, persisting a few months to years (Lupi et al 2013). Juvenile spruce trees could therefore have become larger on high than low disturbance sites, and remained more robust to environmental extremes, which may partially account for lower survival at low disturbance sites.

Relatively poor planted spruce performance at low disturbance sites may be explained by soil texture. High clay content can reduce soil aeration, inhibit fine and potentially coarser root growth, and reduce access to below ground resources (Landhäusser et al 2003, Galipeau et al 1997). Another key factor is competition. Regenerating aspen performance was significantly greater at low than high disturbance sites. Protection of the forest floor is the main benefit of iced-in construction for aspen regeneration due to retention of intact roots (Bachmann et al 2015). Regenerating aspen can suppress spruce growth and require intensive management for joint white spruce and mixedwood development (Pitt et al 2010, Frey et al 2003a).

Navratil and MacIsaac (1996) determined deciduous tree competition alone cannot adequately explain impediments to planted spruce growth. Grass and shrub competition in early growth stages can be more suppressive (Pitt et al 2010). Planted spruce competed with intact roots of perennial shrubs, forbs, and grasses at low disturbance sites, and therefore likely had reduced access to resources from seedling through juvenile stages. Compared to early successional perennials, white spruce are poor competitors for available nitrogen (Gärtner et al 2011), growing space, and soil water (Morris and MacDonald 1991). With high disturbance newly planted spruce would have been competing with plants from seed and newly establishing perennials. Spruce were thus shielded from serious competition for at least a year..

Construction methods were applied based on local topographic features. Low disturbance methods were applied where sites were relatively flat. Where sites had a slope greater than 8˚, excavation was used to create a level construction surface. Greatest spruce growth response metrics occurred not only within the high disturbance treatment, but within sites that were locally topographically heterogeneous, and may therefore have benefitted from upslope contributions of water and nutrients. Although these metrics were not measured over time, it is possible that long term spruce responses to high versus low soil disturbance treatments in this investigation may be confounded by inherent edaphic conditions.

Planted spruce responses varied with soil storage methods and wood treatments. Spruce planted on soils piled separately and overtopped with spread slash responded less favourably than trees planted in soils progressively piled or treated with windrowed slash. Overall performance of planted spruce was better in soils that were progressively piled. More litter and LFH material were likely incorporated into the soil during stockpiling and replacement at progressively piled soil sites, and available nitrogen was greater with separate soil piling. Nitrogen has long been considered the most limiting factor in boreal plant growth (Lupi et al 2013). Although there was a net nitrogen gain in separately piled soils, which may be expected when soil mixing creates a nutrient flush (mineralization) (Vitousek et al 1979, Vitousek and Melillo 1979), planted spruce performed better in soils with lower nitrogen than carbon.

Piled soils, no longer thermally protected by layers of snow and organic material, are exposed to the atmosphere and low temperature, and thereby lose microbial and faunal populations to desiccation (Visser et al 1984). With a greater soil surface area exposed, losses of soil microorganisms and biota to desiccation may have rendered separately piled soils less productive than progressively piled soils post reclamation. Lower nitrogen in progressively piled soils is likely due to greater mixing and incorporation of carbon throughout the soil profile, increasing microbial activity as observed by Vitousek et al (1992), and the greater amount of surviving soil biota consuming the available nitrogen. Greater spruce growth in the progressive pile treatment was likely in response to substantially higher local availability of potassium and phosphorus, and greater soil productivity.

Soils in the duff stripping treatment were likely similarly affected. Mineral soils are typically insulated from the atmosphere by the duff layer. Stripping the duff layer would expose the mineral layer along with the microorganisms and invertebrates within. Soil biota within the duff layer would be even more susceptible to atmospheric conditions stored in relatively porous duff material, and not protected by a more dense soil matrix. There were likely significant losses of detrivores, and microbial activity in the soil. Duff removal or scalping can reduce microbial respiration in soils (Mallik and Hu 1997). Duff stripping tended to have lower survival rates and slower growth of planted spruce.

6. CONCLUSIONS

Little difference was found in survival and growth of planted spruce between treatments, although spruce responded more favourably where soil mixing occurred. Tree species composition on regenerating oil sands exploration sites is inconsistent with regeneration on comparably disturbed areas associated with forest harvest (clear cutting).

Aspen regeneration decreased with increasing soil disturbance. Aspen in the low disturbance treatment regenerated at relatively higher densities because their root systems were left intact. In contrast, the high disturbance treatment impacted aspen by fragmentation of roots, removal of clonal growth support and displacement of fragments. Disturbance intensity increasingly favoured more competitive species (poplar), simultaneously reducing aspen presence on the landscape, and reducing the likelihood of sucker survival. Aspen canopy gaps may persist through several natural disturbances before successful reestablishment of clonal root systems.

More severe disturbance of forest may have resulted in loss of tree seeds and/or propagules leading to low tree regeneration densities insufficient for forest reestablishment. Exposure of soils to the atmosphere and low temperatures may reduce soil fauna and bacteria. Soil productivity can be hampered by soil microbial and invertebrate population losses, directly affecting tree re-establishment, and long term growth and survival of planted spruce and regenerating aspen. Soils with reduced productivity may have led to seedling and sucker demise and low canopy cover uncharacteristic of early successional boreal forest. Root salvage provides protection of aspen roots and soil biota similar to conventional stripping with progressive piling, which reduces soil surface exposure during storage. Unlike conventional stripping with progressive piling, root salvage may promote mixedwood development. The second pass in root salvage was piled separately, but may have been of better use as insulation over top the first pass as in progressive piling. This may have improved aspen regeneration density in root salvage relative to the progressively piled two-pass stripping treatment.

Wood treatments were influential in tree regeneration. Mulch can protect soils and aspen roots from compaction, but may hinder regeneration density with increasing mulch depth. Mulch applied over very well drained (sandy) soil appeared deleterious to planted spruce survival and growth. Although mulch can retain subsurface soil water, the reflective heat it produces in the absence of sufficient water in well drained areas may increase transpiration stress in planted spruce to impact survival over the long term. Nonetheless, it may provide a suitable germination substrate for spruce, whose numbers may increase by including cones or seeds in mulch. However, mulch reduces the ability of many other plant species to germinate or survive. Seeds and propagules may respond better to non-continuous woody debris surface cover.

Retention and redistribution of whole slash after low disturbance site abandonment, rather than mulch may result in better plant community regrowth, more similar to post harvest conditions. Windrowing as an alternative to spreading woody debris reduces the area of soil surface in direct contact with woody material. This may encourage soil warming and stimulate aspen suckering. Warmer soils may stimulate microbial recovery and increase soil productivity. Non-vascular plants may be beneficial to aspen regeneration by reducing germination space for competing vegetation. These combined effects may benefit aspen recovery after high soil disturbance and damage to root systems.

There were many sites where planted spruce and regenerating aspen can achieve simultaneous re-forestation, but there is difficulty associated with managing soil disturbance and woody debris for both species. Although low disturbance methods are cost effective for industry and the environment, high disturbance methods may be necessary for site construction. Early growth of planted spruce is augmented and regenerating aspen impacted by soil disturbance.

This is a concern in Alberta boreal forest where managing for mixedwoods is a high priority. Where sites are located in a Forest Management Agreement area, if high disturbance methods are used, tree volumes may not produce outcomes that meet projected forest harvest goals. Low disturbance methods may more appropriately meet ecological goals, and maintain healthy aspen stands for future harvest. High disturbance methods may be suitable where spruce planting is deemed necessary to fulfill anticipated softwood demand, but this may come at the ecological cost of distortion of native plant communities. Therefore, delineation of clear end land use objectives prior to disturbance is crucial to appropriately select construction and reclamation practices to meet ecologic and economic goals. If soil disturbance is necessary, minimizing soil surface area exposure during storage could protect plant propagules and soil biota.

Treatment applications are commonly determined by construction feasibility based on local topographic conditions and residual woody debris volume. Low disturbance methods are generally lower cost than excavation, and can be successfully implemented on sites of moderate topographic variation, thereby reducing exploration costs and impacts to aspen root systems. Constructing without a mulch footprint could further reduce disturbance and produce regeneration densities similar to post harvest scenarios.

Mulch use should be avoided in well drained soils if spruce planting is part of the reclamation plan; whole slash is now commonly redistributed as part of reclamation, and may increase spruce establishment. Variation in woody debris distribution such that some areas are evenly spread and others windrowed or somewhat piled, with bare areas between, may encourage establishment of non-vascular species; this in turn may positively influence soil productivity, forest recovery and aspen regeneration density.

Where excavation is unavoidable, a thorough site assessment should be conducted to determine potential impacts of construction and woody material management methods. Soil storage methods should be applied to limit soil surface area exposure as this may impact soil biota and plant propagules. This could impact post reclamation soil and vegetation rehabilitation; without which sites are at risk of not achieving adequate canopy capture and returning to productive mixedwood forest.

8. LITERATURE CITED

Abrahamson, I. 2015. Picea glauca, white spruce. In: Fire effects information system, United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). On line at http://www.fs.fed.us/database/feis/plants/tree/picgla/all.html. Accessed 2 December 2016.

Archibold, OW, C Acton and EA Ripley. 2000. Effect of site preparation on soil properties and vegetation cover and the growth and survival of white spruce (Picea glauca) seedlings, in Saskatchewan. Forest Ecology and Management 131:127-141.

Ashworth, J and K Mrazek. 1995. Modified Kelowna test for available phosphorus and potassium in soil. Communications in Soil Science and Plant Analysis 26:731-739.

Bachmann, S, VJ Lieffers and SM Ländhausser. 2015. Forest floor protection during drilling pad construction promotes resprouting of aspen. Ecological Engineering 75:9-15.

Beach, EW and CB Halpern. 2001. Controls on conifer regeneration in managed riparian forests: effects of seed source, substrate, and vegetation. Canadian Journal of Forest Research 31:471-482.

Beckingham, JD. 1993. Ecosystem associations of Northern Alberta. Department of Environmental Protection, Alberta Forest Service. Edmonton Alberta.

Beckingham, JD and JH Archibald. 1996. Field guide to ecosites of northern Alberta. Natural Resources Canada and Canadian Forest Service, Northwest Region, Northern Forestry Centre. Edmonton Alberta. Special Report 5.

Berger, AL, KJ Puettmann and GE Host. 2004. Harvesting impacts on soil and understory vegetation: the influence of season of harvest and within-site disturbance patterns on clear-cut aspen stands in Minnesota. Canadian Journal of Forest Research 34:2159-2168.

Blake, GR. 1965. Bulk density. Pages 374-390 In: CA Black (ed). In: Methods of soil analysis, part 1. American Society of Agronomy. Monograph 9. Madison Wisconsin.

Boateng, JO, JL Heineman, J McClarnon and L Bedford. 2006. Twenty year responses of white spruce to mechanical site preparation and early chemical release in boreal region of northeastern British Columbia. Canadian Journal of Forest Research 36:2386-2399.

Boyle, TJB. 1992. Biodiversity of Canadian forests: current status and future challenges. Forestry Chronicle 68:444-453.

Campbell, DJ and JK Henshall (eds). 1991. Bulk Density. In: Soil and environmental analysis. Marcel Dekker. New York United States. Pp.329-366.

Christy, EJ and RN Mack. 1984. Variation in demography of juvenile *Tsuga heterophyla* across the substratum mosaic. Journal of Ecology 72:75-91.

Cole, E, A Youngblood and M Newton. 2003. Effects of competing vegetation on juvenile white spruce (Picea glauca (Moench) Voss) growth in Alaska. Annals of Forest Science 60: 573-583.

Coleman MD, RE Dickson and JG Isebrands. 1998. Growth and physiology of aspen supplied with different fertilizer addition rates. Physiologia Plantarum 103:513-526.

Cooke, BJ and J Roland. 2007. Trembling aspen responses to drought and defoliation by forest tent caterpillar and reconstruction of recent outbreaks in Ontario. Canadian Journal of Forest Research 37:1586-1598.

Day, RJ. 1972. Stand structure, succession and use of southern Alberta's Rocky Mountain Forest. Ecology 53:472-478.

Eis, S. 1967. Establishment and early development of white spruce in the interior of British Columbia. Forestry Chronicle 43:174-177.

Environment and Sustainable Resource Development (ESRD). 2009. Management of wood chips on public land. Lands Division, Land Management Branch, Petroleum Land Use and Reclamation Section, Government of Alberta. Industry Directive Number: ID 2009-01. Edmonton Alberta. 2 pp.

Forest Research Advisory Council of Canada. 1994. Forest research priorities in Canada, 1993. Forestry Chronicle 70:84-87.

Fraser, EC, VJ Lieffers and SM Landhausser. 2004. Wounding of aspen roots promotes suckering. Canadian Journal of Botany 82:310-315.

Frey, BR, VJ Lieffers, SM Landhäusser, PG Comeau and KJ Greenway. 2003a. An analysis of sucker regeneration of trembling aspen. Canadian Journal of Forest Research 33:1170-1176.

Frey, BR, VJ Lieffers, AD Munson and PV Blenis. 2003b. The influence of partial harvesting and forest floor disturbance on nutrient availability and understory vegetation in boreal mixedwoods. Canadian Journal of Forest Research 33:1180-1188.

Galipeau, C, D Kneeshaw and Y Bergeron. 1997. White spruce and balsam fir colonization of a site in the southeastern boreal forest as observed 68 years after fire. Canadian Journal of Forest Research 27:139-147.

Gärtner, SM, VJ Lieffers and SE Macdonald. 2011. Ecology and management of natural regeneration of white spruce in the boreal forest. Environmental Review 19:461-478.

Global Forest Watch Canada (2005). 2005 natural regions and Subregions of Alberta [map]. Scale not given. In: Maps – the last great intact forest landscapes of Canada: Atlas of Alberta: Part 1. On line at http://global forestwatch.ca/publications/20090402A_MapsI. Accessed 15 December 2016.

Gold, K and F Hay. 2014. Identifying desiccation-sensitive seeds. Millennium Seed Bank Partnership, Technical Information Sheet 10. Royal Botanic Gardens, Kew Victoria Australia. On line at http://www.kew.org/sites/default/files/10-Desiccation%20tolerance%20web_0.pdf. Accessed 29 October 2016.

Gradowski, T, D Sidders, T Keddy, VJ Lieffers and SM Landhäusser. 2008. Effects of overstory retention and site preparation on growth of planted white spruce seedlings in deciduous and coniferous dominated boreal plains mixedwoods. Forest Ecology and Management 255:3744-3749.

Grover G, and W Fast. 2007. Alberta making strides in mixedwood management. Forestry Chronicle 83: 714-718.

Harris, HT. 1990. Populus balsamifera subsp. balsamifera. In: Fire effects information system, United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available at http://www.fs.fed.us/database/feis/tree/popbalb/all.html. Accessed 3 December 2016.

Hart, SA and HYH Chen. 2006. Understory vegetation dynamics of North American boreal forests. Critical Reviews in Plant Sciences 25:381-397.

Hogg, EH, JP Brandt and B Kochtubajda. 2002. Growth and dieback of aspen forests in northwestern Alberta, Canada, in relation to climate and insects. Canadian Journal of Forest Research 32:823-832.

Howat, DR, 2000. Acceptable salinity, sodicity and pH values for boreal forest reclamation. Alberta Environment, Environmental Sciences Division, Edmonton Alberta. Report # ESD/LM/00-2. or ISBN 0-7785-1174-X. 191 pp.

Kabzems, R and S Haeussler. 2005. Soil properties, aspen, and white spruce responses 5 years after organic matter removal and compaction treatments. Canadian Journal of Forest Research 35: 2045-2055.

Kroetsch, D and C Wang. 2008. Particle size distribution. Pages 713-725 In: MR Carter and EG Gregorich (eds). Soil sampling and methods of analysis. Canadian Society of Soil Science. CRC Press. Boca Raton Florida.

Landhäusser, SM and VJ Lieffers. 1998. Growth of Populus tremuloides in association with Calamagrostis canadensis. Canadian Journal of Forest Research 28:396-401.

Landhäusser, SM, VJ Lieffers and P Chow. 2007. Impact of chipping residues and its leachate on the initiation and growth of aspen root suckers. Canadian Journal of Soil Science 87:361-367.

Landhäusser, SM, VJ Lieffers and U Silins. 2003. Utilizing pioneer species as a hydrological nurse crop to lower water table for reforestation of poorly drained boreal sites. Annals of Forest Science 60:741-748.

Landhäusser, SM, J Wachowski and VJ Lieffers. 2015. Transfer of live aspen root fragments, an effective tool for large-scale boreal forest reclamation. Canadian Journal of Forest Research 45:1056-1064.

LaRoi, GH and MHL Stringer. 1976. Ecological studies in the boreal spruce-fir forests of the North American taiga, II. Analysis of the bryophyte flora. Canadian Journal of Botany 54:619-643.

Laverty, DH and A Bollo-Kamara. 1988. Recommended methods of soil analyses for Canadian prairie agricultural soils. Report 300. Alberta Agriculture. Edmonton Alberta.

Lieffers, VJ, SE Macdonald and EH Hogg. 1993. Ecology of and control strategies for Calamagrostis canadensis in boreal forest sites. Canadian Journal of Forest Research 23:2070-2077.

Loeppert, RH and DL Suarez. 1996. Gravimetric method for loss of carbon dioxide. Pages 455-456 In: JM Bartels et al (eds). Methods of soil analysis: part 3 chemical methods. American Society of Agronomy and Soil Science Society of America. Madison Wisconsin.

Lupi, C, H Morin, A Deslauriers, S Rossi and D Houle. 2013. The role of soil nitrogen for the conifers of the boreal forest: a critical review. International Journal of Plant and Soil Science 2:155-189.

MacDonald, GB. 1995. The case for boreal mixedwood management: An Ontario perspective. Forestry Chronicle 71:725-733.

Mackenzie, DD. 2013. Oil sands mine reclamation using boreal forest surface soil (LFH) in northern Alberta. PhD dissertation. Department of Renewable Resources, University of Alberta. Edmonton Alberta. 240 pp.

Mallik, AU and D Hu. 1997. Soil respiration following site preparation treatments in boreal mixedwood forest. Forest Ecology and Management 97:265-275.

Michaelian, M, EH Hogg, RJ Hall and E Arsenault. 2011. Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. Global Change Biology 17: 2084–2094.

Miller, JJ and D Curtin. 2008. Electrical conductivity and soluble ions. Pages 161-172 In MR Carter and EG Gregorich (eds). Soil sampling and methods of analysis. Canadian Society of Soil Science and CRC Press. Boca Raton Florida.

Miller MR and SW May. 1979. Below-ground ecosystems project. Pages 64-70 In: Land Reclamation Program, Annual Report. 1978. Argonne National Laboratory, United States Department of Agriculture.

Morris, DM and GB MacDonald. 1991. Development of a competition index for young conifer plantations established on boreal mixedwood sites. Forestry Chronicle 67:403-410.

Munson, AD, HA Margolis and DG Brand. 1993. Intensive silvicultural treatment: impacts on soil fertility and planted conifer response. Soil Science Society of America Journal 57:246-255.

Natural Regions Committee 2006. Natural regions and subregions of Alberta. Compiled by DJ Downing and WW Pettapiece. Government of Alberta. Pub. No. T/852. Edmonton Alberta.

Navratil, S and DA MacIsaac. 1996. Juvenile growth of white spruce and deciduous competition on mixedwood sites in Alberta. Canadian Forest Service, Northern Forestry Centre. Edmonton Alberta. 116 pp.

Nelson, DW and LE Sommers. 1996. Total carbon, organic carbon and organic matter. Pages 961-1010 In: JM Bartels et al (eds). Methods of soil analysis: part 3 chemical methods. American Society of Agronomy and Soil Science Society of America. Madison Wisconsin.

Osko, T and M Glasgow. 2010. Removing the wellsite footprint: recommended practices for construction and reclamation of wellsites on upland forests in boreal Alberta. Department of Biological Sciences, University of Alberta, Edmonton Alberta. 61 pp.

Peters, VS, SE Macdonald and RT Dale. 2006. Patterns of initial versus delayed regeneration of white spruce in boreal mixedwood succession. Canadian Journal of Forest Research 36:1597-1609.

Pinno, BD, SM Landhäusser, MD MacKenzie, SA Quideau and PS Chow. 2012. Trembling aspen seedling establishment, growth and response to fertilization on contrasting soils used in oil sands reclamation. Canadian Journal of Soil Science 92:143-151.

Pitt, DG, PG Comeau, WC Parker, D MacIsaac, S McPherson, MK Hoepting, A Stinson and M Mihajlovich. 2010. Early vegetation control for the regeneration of a single-cohort, intimate mixture of white spruce and trembling aspen on upland boreal sites. Canadian Journal of Forest Research 40:594-564.

Purdy, BG, SE Macdonald and MRT Dale. 2002. The regeneration niche of white spruce following fire in the mixedwood boreal forest. Silva Fennica 36:289-306.

Qi, MQ and JB Scarratt. 1998. Effect of harvesting method on seed bank dynamics in a boreal mixedwood forest in northwestern Ontario. Canadian Journal of Botany 76:872-883.

R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna Austria. URL https://www.R-project.org/.

Renkema, KN, VJ Lieffers and SM Ländhausser. 2009. Aspen regeneration on log decking areas as influenced by season and duration of log storage. New Forests 38:323-335.

Rhodes AC, T Barney and SB St Clair. 2016. Stand composition, tree proximity and size have minimal effects on leaf function of coexisting aspen and subalpine fir. PLoS One 11: article number e0154395.

Rowe, JS. 1972. Forest regions of Canada. Fisheries and Environment Canada, Canadian Forest Service. Publication No.1300. Ottawa Ontario.

Schmidt, MG, SE Macdonald and RL Rothwell. 1996. Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta. Canadian Journal of Soil Science 76:531-540.

Shepperd, WD. 1993. The effects of harvesting activities on soil compaction root damage and suckering in Colorado aspen. Western Journal of Applied Forestry 8:62-66.

Stone, DM and JD Elioff. 1998. Soil properties and aspen development five years after compaction and forest floor removal. Canadian Journal of Soil Science 78:51-58.

Suffling, R, C Lihou and Y Morand. 1988. Control of landscape diversity by catastrophic disturbance: a theory and a case study of fire in a Canadian boreal forest. Environmental Management 12:73-78.

Uchytil, RJ. 1991. Betula papyrifera. In: Fire effects information system, United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available at http://www.fs.fed.us/database/feis/. Accessed 3 December 2016.

United States Department of Agriculture (USDA). 2003. Quaking aspen *Populus tremuloides* Michx. In: Plant guide. United States Department of Agriculture and Natural Resources

Conservation Service. On line at https://plants.usda.gov/plantguide/pdf/cs_potr5.pdf. Accessed 5 June 2016.

Vinge, T and M Pyper. 2012. Managing woody materials on industrial sites. Alberta School of Forest Science and Management, University of Alberta. Edmonton Alberta.

Visser, S, J Fujikawa, CL Griffiths and D Parkinson. 1984. Effect of topsoil storage on microbial activity primary production and decomposition potential. Plant and Soil 82:41-50.

Visser, S, D Maynard and RM Danielson. 1998. Response of ecto- and arbuscular mycorrhizal fungi to clear-cutting and the application of chipped aspen wood in a mixedwood site in Alberta, Canada. Applied Soil Ecology 7:257-269.

Vitousek, PM and JM Melillo.1979. Nitrate losses from disturbed forests: patterns and mechanisms. Forest Science 15:605-619.

Vitousek, PM, SW Andariese, PA Matson, L Morris and RL Sanford. 1992. Effects of harvest intensity, site preparation, and herbicide use on soil nitrogen transformations in a young loblolly pine plantation. Forest Ecology and Management 49: 277-292.

Vitousek, PM, JR Gosz, CC Grier, JM Melillo, WA Reiners and RL Todd. 1979. Nitrate losses from disturbed ecosystems. Science 204:469-474.

Weber, E. 2011. Strong regeneration ability from rhizome fragments in two invasive clonal plants (Solidago canadensis and S. gigantea). Biological Invasions 13:2947-2955.

Zasada, JC and RA Gregory. 1969. Regeneration of white spruce with reference to interior Alaska: a literature review. United States Department of Agriculture and Forest Service Research Paper PNW-79. Pacific Northwest forest and Range Experiment Station, Institute of Northern Forestry, and United States Department of Agriculture. Juneau Alaska. 37 pp.

Table 3.1. Summary of well sites and treatments in the study.

Year Company	Site Location	Soil Treatment	Soil Excavation		Soil Storage Method		Woody Material Management			Trees	
			No	Yes	Progressive Pile	Separate Piles	Mulch Spread	Whole Slash Spread	Whole Slash Wind-rowed	Non-Planted	Planted
2004 – 1	16-31-85-06 06-29-85-06N 06-29-85-06S	Iced-in	√		n/a		√ Shallow & Deep			√	√
2004 – 1	02-19-85-06 05-29-85-06 01-05-86-06 16-05-86-06 11-12-86-07	Iced-in	√		n/a		√			√	√
2005 – 1	11-19-84-06 06-30-84-06	Iced-in	√		n/a			√	√	√	√
2006 – 1	13-25-84-07 16-26-84-07 02-26-84-07	Iced-in	√		n/a		√			√	√
2004 – 2	13-07-82-06 11-17-82-06 14-29-82-06 05-32-82-06 12-23-82-07	Stripped 2 passes		√	√			√		√	√
2005 – 2	03-04-82-06 08-01-83-06	Stripped 2 passes		√	√			√	√	√	√
2006 – 2	02-17-82-06			√	√			√	√	√	√
2006 – 1	02-33-84-07 08-28-84-07 10-26-84-07	Stripped 2 passes		√		√		√	√	√	√
2006 – 2	06-13-82-06 15-11-82-06 12-33-81-06	Duff stripped		√ minimal	√			√		√	√
2006 – 1	2-35-84-07 16-28-84-07 03-33-84-07 14-28-84-07 11-28-84-07 13-22-84-07	Root salvage		√		√		√		√	

Table 3.2. DBH and height class values assigned to regenerating aspen.

DBH Class	DBH (cm)	Height Class	Height (m)
1	0 – 2	1	0 – 0.5
3	2 – 4	2	0.5 – 1.3
5	4 – 6	3	1.3 – 3
7	6 – 9	4	3 – 5
9	9 - 12	5	5 +

Table 3.3. Means and ANOVA results evaluating dominant regenerating trees and regenerating aspen response to harvest (cutblocks) and soil treatments, and planted spruce response to soil treatments including low disturbance with slash or mulch treatments, duff stripping, high disturbance with progressive or separate soil piling, and root salvage treatments, on northern Alberta boreal well sites. ANOVA p-values indicate significant variation between all groups. Differences among least square means are indicated by letters following the mean values.

	Aspen			Planted Spruce		
Treatment (n) means,	Density (stems m^{-2})	DBH Class	Height Class	Height (cm)	DBH (cm)	Survival (%)
ANOVA p-values, df=6	<0.001	0.124	0.034	0.451	0.288	0.270
Cutblock (4)	1.64 a	2.11	3.64 a	-	-	-
Low slash (2)	1.16 ab	1.35	3.18 ab	199.30	14.70	87.0
Low mulch (8)	0.79 bc	1.65	3.11 ab	189.98	13.64	78.4
Duff stripping (3)	0.36 cd	1.00	2.33 ab	176.45	11.15	67.4
Root salvage (6)	0.23 d	1.33	2.16 b	-	-	-
High progressive (8)	0.21 d	1.17	2.55 ab	238.09	21.75	91.9
High separate (3)	0.05 d	1.17	2.76 ab	182.00	11.64	76.7
Standard errors	+/-0.50	+/-0.32	+/-0.47	+/-24.70	+/-4.28	+/-0.02

Treatment (n) means,	Birch (stems m^{-2})	Poplar (stems m^{-2})	Spruce (stems m^{-2})	Total density (stems m^{-2})
ANOVA p-values, df=6	0.003	0.002	0.251	0.003
Cutblock (4)	3.19 a	0.02 b	0.25	5.17 a
Low slash (2)	1.57 ab	0.15 b	0.27	3.15 ab
Low mulch (8)	0.63 b	0.41 b	0.58	2.57 ab
Duff stripping (3)	0.08 b	0.26 b	0.11	0.88 b
Root salvage (6)	0.29 b	2.05 a	0.34	3.08 ab
High progressive (8)	1.17 ab	0.60 b	0.29	2.31 b
High separate (3)	0.05 b	0.99 ab	0.15	1.25 b
Standard errors	+/-0.93	+/-0.66	+/-0.13	+/-1.12

Correlation with total density	Birch	Poplar	Spruce	Aspen
p-value	<0.001	0.753	0.005	0.001
correlation	+0.60	+0.06	+0.47	+0.52

Table 3.4. Means and ANOVA results for selected comparisons of dominant tree species density (stems m^{-2}) and total density of all tree species within soil and wood treatments on northern Alberta boreal well sites. Differences among least square means are indicated by letters following the mean values.

Soil and wood treatments Means and ANOVA	Aspen (stems m^{-2})	Birch (stems m^{-2})	Poplar (stems m^{-2})	Spruce (stems m^{-2})	Total Density (stems m^{-2})
Harvest vs Low disturbance					
p-values, 1df	0.011	0.166	<0.001	0.561	0.033
Cutblock	1.64	3.19	0.01	0.25	5.17
Low disturbance	0.76	1.43	0.25	0.18	2.59
Standard errors	+/-0.21	+/-1.11	+/-0.04	+/-0.12	+/-0.93
Wood treatments in low disturbance					
p-values, 2 df	0.691	0.002	0.003	0.031	0.961
Mulch	1.15	0.04b	0.88a	0.90a	3.15
Spread slash	1.05	1.63a	0.08b	0.28ab	3.03
Windrowed slash	1.28	1.50a	0.24b	0.25b	3.26
Standard errors	+/-0.09	+/-0.75	+/-0.37	+/-0.32	+/-0.09
High and low disturbance vs duff stripping					
p-values, 2 df	0.001	0.003	0.131	0.014	0.003
Low disturbance	0.57a	0.98a	0.13	0.39a	2.23a
High disturbance	0.16b	1.45a	0.21	0.31a	2.17a
Duff stripping	0.36ab	0.08b	0.26	0.11b	0.88b
Standard errors	+/-0.18	+/-0.52	+/-0.05	+/-0.11	+/-0.20
High disturbance vs root salvage					
p-values, 1 df	0.655	0.048	<0.001	0.409	0.324
High disturbance	0.16	1.43	0.21	0.31	2.17
Root salvage	0.23	0.29	2.05	0.34	3.09
Standard errors	+/-0.12	+/-0.57	+/-0.92	+/-0.02	+/-0.45
Progressive vs Separate soil pile treatments					
p-values, 7 df	0.002	0.001	0.424	0.160	0.019
Progressive	0.29	0.73	1.25	0.27	2.55
Separate	0.05	0.05	0.99	0.15	1.25
Standard errors	+/-0.13	+/-0.16	+/-0.75	+/-0.18	+/-0.65
Wood treatments within soil pile treatments					
p-values, 6 df	0.791	0.282	0.221	0.061	0.685
Spread	0.14	0.33	1.15	0.13	1.76
Windrow	0.20	0.46	1.10	0.28	2.04
Standard errors	+/-0.11	+/-0.06	+/-0.53	+/-0.18	+/-0.24
Soil pile * Wood treatments					
p-values, 6 df	0.067	0.508	0.059	0.885	0.217
Progressive spread	0.27a	0.62	1.60a	0.18	2.66
Progressive windrow	0.33a	0.84	0.91a	0.36	2.44
Separate spread	0.02b	0.03	0.70a	0.09	0.87
Separate windrow	0.08ab	0.08	1.28a	0.20	1.64
Standard errors	+/-0.16	+/-0.16	+/-0.75	+/-0.18	+/-0.24

Table 3.5. Means and one-way ANOVA results for comparisons of response to high (n=5) versus low (n=5) soil disturbance treatments in planted spruce height, DBH and percent survival, and two-way ANOVA including planting treatment results for regenerating aspen density, DBH and height on northern Alberta boreal well sites.

	Planted Spruce			
Means and ANOVA	Height (cm)	DBH (cm)	Survival (%)	MANOVA, 6 df
Soil treatment				
p-values, 8 df	0.161	0.113	0.088	0.106
High	264.89	24.0	91.25	
Low	195.07	15.1	75.42	
Standard errors	+/-45.18	+/-6.50	+/-9.50	

	Regenerating Aspen			
Means and ANOVA	Density (stems m^{-2})	DBH Class	Height Class	MANOVA, 4 df
Soil treatment				
p-values, 14, 9, 13 df	0.007	0.025	0.030	0.065
High	0.16	1.00	2.34	
Low	0.57	1.65	3.19	
Standard errors	+/-0.17	+/-0.42	+/-0.17	
Planting treatment				
p-values, 10, 9, 8 df	0.959	0.706	0.393	0.095
Planted	0.49	1.32	2.66	
Non-planted	0.24	1.45	3.04	
Standard errors	+/-0.07	+/-0.04	+/-0.21	
Soil * Planting				
p-values, 10, 9, 8 df	0.007	0.902	0.922	0.073
High planted	0.14b	1.00	2.08	
High non-planted	0.17b	1.00	2.51	
Low planted	0.84a	1.58	3.23	
Low non-planted	0.30b	1.72	3.42	
Standard errors	+/-0.13	+/-0.04	+/-0.47	

Table 3.6. Means and ANOVA results for comparisons of planted spruce height, DBH and survival, and regenerating aspen density, DBH, and height response to low soil disturbance (n=5) versus duff stripping (n=3), and high soil disturbance (n=5) versus duff stripping on northern Alberta boreal well sites. Differences among least square means are indicated by letters following the mean values.

	Planted Spruce			
Means and ANOVA	Height (cm)	DBH (cm)	Survival (%)	MANOVA, 4 df
Soil treatment				
p-values; 6 df	0.103	0.063	0.198	0.198
High disturbance	264.9	26.6	91.3	
Duff stripping	176.5	11.2	67.4	
Standard errors	+/-46.0	+/-6.8	+/-16.5	
Soil treatment				
p-values; 6 df	0.772	0.642	0.707	0.591
Low disturbance	195.07	15.08	75.4	
Duff stripping	176.45	11.15	67.4	
Standard errors	+/-61.40	+/-8.02	+/-20.4	

	Regenerating Aspen			
Means and ANOVA	Density (stems m^{-2})	DBH Class	Height Class	MANOVA, 4 df
Soil treatment (High vs Duff)				
p-values, 10, 1, 1 df	0.196	1.000	0.726	0.292
High disturbance	0.16	1.00	2.27	
Duff stripping	0.36	1.00	2.33	
Standard errors	+/-0.21	+/-0.00	+/-0.40	
Planting treatment:: 6, 1, 1 df	0.433	1.000	0.784	0.781
Soil * Planting: 6, 1, 1 df	0.456	1.000	0.307	0.245
Soil treatment (Low vs Duff)				
p-values, 10, 16, 11 df	0.094	0.114	0.112	0.094
Low disturbance	0.57	1.75	3.32	
Duff stripping	0.36	1.00	2.33	
Standard errors	+/-0.19	+/-0.41	+/-0.48	
Planting p-values, 8 df	0.886	1.000	0.729	0.232
Soil * Planting p-values, 8 df	0.026	0.555	0.580	0.678
Low planted	0.88a	1.61	3.23	
Low non-planted	0.30a	1.90	3.42	
Duff planted	0.43a	1.00	2.42	
Duff non-planted	0.28a	1.00	2.23	
Standard errors	+/-0.23	+/-0.39	+/-0.67	

Table 3.7. Means and ANOVA results for comparisons of soil physical and chemical characteristics differing between duff stripping (n=3) and high (n=5) and low (n=5) disturbance treatments, and duff stripping treatment and controls on northern Alberta boreal well sites. Differences among least square means are indicated by letters following the mean values.

Between Soil Treatments							
Means and ANOVA	C:N ratio	Total Organic Carbon	Nitrogen (mg/kg)	Organic Matter (%)	Sand (%)	Silt (%)	Clay (%)
6 cm depth							
p-values, 2 df	<0.001	-	-	-	<0.001	<0.001	<0.001
High disturbance	20.7a	-	-	-	59.8a	17.9b	22.4b
Low disturbance	22.4a	-	-	-	50.9a	14.0b	35.1a
Duff stripping	13.7b	-	-	-	36.9b	48.3a	14.8b
Standard errors	+/-5.6	-	-	-	+/-10.4	+/-17.0	+/-9.2
30 cm depth							
p-values, 2 df	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	-
High disturbance	20.7a	2.19a	0.110a	4.3a	57.9a	16.8b	-
Low disturbance	23.3a	0.72b	0.035b	1.4b	52.7a	19.3b	-
Duff stripping	10.1b	0.78b	0.056b	1.6b	37.3b	40.2a	-
Standard errors	+/-6.1	+/-0.73	+/-0.03	+/-1.5	+/-9.4	+/-11.3	-

Between Duff Stripping and Control						
Means and ANOVA	C:N ratio	Total Organic Carbon	Nitrogen (mg/kg)	Organic Matter (%)	Clay (%)	Potassium (mg/kg)
6 cm depth						
p-values, 2 df	0.006	-	-	-	0.042	0.044
Control	7.6	-	-	-	11.3	58.5
Duff stripping	13.7	-	-	-	14.8	119.1
Standard errors	+/-3.2	-	-	-	+/-0.4	+/-32.3
30 cm depth						
p-values, 2 df	0.022	0.071	0.067	0.079	-	-
Control	7.5	0.23	0.031	0.5	-	-
Duff stripping	10.1	0.78	0.056	1.6	-	-
Standard errors	+/-1.3	+/-0.28	+/-0.003	+/-0.5	-	-

Table 3.8. Means and ANOVA results for comparisons of regenerating aspen density, DBH and height response to cutblock (n=4) versus low soil disturbance (n=4), root salvage (n=6) versus high soil disturbance (n=5) and comparisons of soil physical and chemical properties at 6 and 30 cm depths that differ between root salvage and high disturbance sites, and root salvage and controls on northern Alberta boreal well sites.

	Regenerating Aspen			
Means and ANOVA	Density (stems m^{-2})	DBH Class	Height Class	MANOVA, 3df
Soil treatment				
p-values, 4, 4 , 8 df	0.011	0.009	0.446	0.097
Cutblock	1.64	2.11	3.64	
Low disturbance	0.76	2.97	3.88	
Standard errors	+/-0.21	+/-0.18	+/-0.26	
Soil treatment				
p-values, 9 df	0.655	0.333	0.500	0.419
High disturbance	0.17	1.00	2.51	
Root salvage	0.23	1.33	2.16	
Standard errors	+/-0.12	+/-0.43	+/-0.75	

			Soils		
Between root salvage and high disturbance treatments					
Means and ANOVA	Clay (%)	Silt (%)	C:N ratio	EC (dS/m)	pH
6 cm depth					
p-values, 1 df	0.004	<0.001	0.098	0.002	0.043
High disturbance	25.36	16.76	20.67	0.182	6.12
Root salvage	14.57	37.63	17.49	0.497	6.57
Standard errors	+/-1.90	+/-12.19	+/-3.92	+/-0.184	+/-0.26
30 cm depth					
p-values, 1 df	0.057	0.011	0.008	0.073	-
High disturbance	22.38	17.86	20.72	0.206	-
Root salvage	16.13	31.07	15.69	0.357	-
Standard errors	+/-3.65	+/-2.98	+/-3.52	+/-0.088	-
Between root salvage and control					
Means and ANOVA	Clay (%)	S (mg/kg)	C:N ratio	EC (dS/m)	pH
6 cm depth					
p-values, 1 df	0.002	-	0.004	0.027	<0.001
Control	11.0	-	13.93	0.202	5.27
Root salvage	14.6	-	17.49	0.497	6.57
Standard errors	+/-1.78		+/-1.78	+/-0.149	+/-0.65
30 cm depth					
p-values, 1 df	-	0.012	0.014	0.022	0.004
Control	-	2.0	10.98	0.144	5.28
Root salvage	-	5.3	15.70	0.357	6.66
p-values		+/-1.65	+/-2.36	+/-0.106	+/-0.69

Table 3.9. Means and two-way ANOVA results for comparisons of planted spruce height, DBH and percent survival in progressive (n=3) versus separate (n=3) soil pile treatments and spread versus windrowed slash treatments; comparisons of soil physical and chemical properties differing between progressive and separate soil pile treatments and of soil properties differing between spread and windrowed slash treatments in the separate soil pile treatment on northern Alberta boreal well sites. Differences among least square means are indicated by letters following the mean values.

	Planted Spruce			
Means and ANOVA	Height (cm)	DBH (cm)	Survival (%)	MANOVA, 3 df
Soil pile treatment				
p-values; 7, 7, 6 df	0.269	0.187	0.626	0.666
Progressive	193.4	13.62	93.1	
Separate	182.0	11.64	76.7	
Standard errors	+/-24.4	+/-3.26	+/-14.5	
Wood treatment				
p-values; 6, 6, 4 df	0.572	0.154	0.116	0.288
Spread	182.08	12.39	83.0	
Windrow	193.33	12.87	86.8	
Standard errors	+/-10.89	+/-1.41	+/-7.1	
Soil * Wood				
p-values 6, 6, 4 df	0.061	0.031	0.337	0.516
Progressive spread	196.67a	14.76a	93.1	
Progressive windrow	190.17a	12.47a	93.1	
Separate spread	167.50a	10.01a	72.9	
Separate windrow	196.50a	13.27a	80.6	
Standard errors	+/-15.39	+/-1.99	+/-10.0	

	Regenerating Aspen			
Means and ANOVA	Density (stems m^{-2})	DBH Class	Height class	MANOVA, 3 df
Soil pile treatment				
p-values, 11, 10, 10 df	0.002	0.834	0.333	0.099
Progressive	0.29	1.40	2.85	
Separate	0.07	1.00	2.64	
Standard errors	+/-0.13	+/-0.28	+/-0.45	
Wood treatment				
p-values, 6, 4, 5 df	0.791	0.090	0.668	0.051
Spread	0.21	1.74	2.82	
Windrow	0.20	1.07	2.68	
Standard errors	+/-0.11	+/-0.30	+/-0.18	
Soil * Wood				
p-values, 6, 5, 6 df	0.067	0.423	0.390	0.336
Progressive spread	0.27a	1.67	2.58	
Progressive windrow	0.33a	1.14	3.12	
Separate spread	0.02b	2.00	2.58	
Separate windrow	0.08ab	1.00	2.52	
Standard errors	+/-0.16	+/-0.30	+/-0.39	

Table 3.10. Means and two-way ANOVA results for comparisons of soil physical and chemical properties differing between progressive (n=3) and separate (n=3) soil pile treatments, separate and progressive forested controls, and comparisons of soil properties differing between spread and windrowed slash treatments within the separate soil pile treatment on northern Alberta boreal well sites.

Means and ANOVA	C:N ratio	Total Organic Carbon (%)	Organic Matter (%)	Clay (%)	Nitrogen (mg/kg)	Phosphorus (mg/kg)	Potassium (mg/kg)	Electrical Conductivity (dS/m)	pH
Between soil pile treatments									
6 cm depth									
p-values; 2 df	0.019	0.272	0.259	0.002	0.396	0.001	0.005	0.006	0.241
Progressive	17.7	3.8	7.6	23.9	0.20	31.8	202.5	0.618	6.15
Separate	13.1	1.9	3.8	17.1	0.13	12.5	114.2	0.284	5.89
Standard errors	+/-2.3	+/-0.9	+/-1.9	+/-3.3	+/-0.04	+/-9.7	+/-44.2	+/-0.167	+/-0.13
30 cm depth									
p-values: 2 df	0.695	0.839	0.906	0.041	0.605	0.002	0.001	<0.001	0.031
Progressive	9.3	0.8	1.4	24.6	0.11	20.0	163.1	0.373	6.43
Separate	8.9	0.8	1.5	20.0	0.08	8.5	108.3	0.176	5.87
Standard errors	+/-0.2	+/-0.1	+/-0.1	+/-2.3	+/-0.01	+/-5.8	+/-27.4	+/-0.10	+/-0.28
Between treatment forested controls									
Means and ANOVA									
6 cm depth									
p-values; 2 df	0.395	0.156	0.110	0.043	0.077	0.194	0.024	0.071	0.101
Progressive control	11.7	0.3	7.5	17.6	0.24	20.7	118.1	0.374	6.03
Separate control	9.8	0.8	1.0	13.9	0.05	11.4	63.1	0.166	5.43
Standard errors	+/-0.8	+/-0.6	+/-1.4	+/-1.8	+/-0.04	+/-4.6	+/-27.9	+/-0.076	+/-0.28
30 cm depth									
p-values: 2 df	0.320	0.274	0.302	0.041	0.212	0.921	0.025	0.108	0.486
Progressive control	8.3	1.5	2.9	26.0	0.18	9.3	142.5	0.340	6.03
Separate control	7.3	0.3	0.5	17.5	0.03	9.8	76.4	0.142	5.75
Standard errors	+/-0.5	+/-0.6	+/-1.2	+/-4.0	+/-0.01	+/-0.2	+/-32.3	+/-0.10	+/-0.13

Within separate soil pile treatment	Soils	Ground cover	
Means and ANOVA	Potassium (mg/kg)	Slash (%)	Moss (%)
6 cm depth			
p-values; 2 df	0.056	0.025	0.005
Spread	95.0	16.3	12.8
Windrow	133.3	10.9	18.1
Standard error	+/-19.16	+/-1.86	+/-2.41

Table 3.11. Means and contrast results for comparisons of planted spruce height, DBH and survival and regenerating aspen density, DBH and height response to mulch (n=3), spread (n=2) and windrowed slash (n=2) treatments within low soil disturbance treatments on northern Alberta boreal well sites.

	Planted Spruce			
Wood treatments Means and contrasts	Height (cm)	DBH (cm)	Survival (%)	MANOVA, 1 df
Mulch vs Spread Slash				
p-values, 4, df	0.745	0.588	0.402	-
Mulch	181.60	11.25	83.4	
Spread slash	194.63	14.17	93.8	
Standard errors	+/-37.32	+/-4.98	+/-11.0	
Mulch vs Windrowed Slash				
p-values, 4 df	0.609	0.507	0.786	-
Mulch	181.60	11.25	83.4	
Windrowed slash	202.25	14.87	80.2	
Standard errors	+/-37.32	+/-4.98	+/-11.0	
Spread vs Windrowed Slash				
p-values, 4 df	0.861	0.904	0.326	0.508
Spread slash	194.63	14.17	93.8	
Windrowed slash	202.25	14.87	80.2	
Standard errors	+/-40.88	+/-5.45	+/-12.1	

	Regenerating Aspen			
Wood treatments Means and contrasts	Density (stems m^{-2})	DBH Class	Height Class	MANOVA, 6, 3 df
Mulch vs Spread Slash				
p-values,11 df	0.700	0.242	0.625	-
Mulch	1.15	1.63	2.98	
Spread slash	1.05	1.23	3.13	
Standard errors	+/-0.25	+/-0.32	+/-0.30	
Mulch vs Windrowed Slash				
p-values,11 df	0.630	0.596	0.404	-
Mulch	1.15	1.63	2.98	
Windrowed slash	1.28	1.46	3.24	
Standard errors	+/-0.25	+/-0.32	+/-0.30	
Spread vs Windrowed Slash				
p-values,11 df	0.433	0.541	0.745	0.673
Spread slash	1.05	1.23	3.13	
Windrowed slash	1.28	1.46	3.24	
Standard errors	+/-0.28	+/-0.35	+/-0.33	
Planting treatment				
p-values, 8df	0.756	0.843	0.981	0.991
Planted	1.19	1.48	3.10	
Non-planted	1.13	1.46	3.10	
Standard errors	+/-0.18	+/-0.12	+/-0.12	

Table 3.12. Means and ANOVA results for comparisons of soil physical and chemical properties differing with mulch (n=3) versus spread (n=2) versus windrowed (n=2) slash treatments within the low disturbance treatment on northern Alberta boreal well sites.

Wood treatments Means and contrasts	Bulk Density	Water (%)	Sand (%)	Clay (%)	Potassium (mg/kg)	Sulphur (mg/kg)	TOC	Electrical Conductivity (dS/m)	pH
6 cm depth									
p-values, 2, df	0.031	0.068	0.035	-	0.074	0.005	-	0.004	0.004
Mulch	1.44a	0.18a	35.3a	-	48.3a	5.0b	-	0.079b	5.28a
Spread slash	1.23b	0.15ab	24.7ab	-	67.5a	6.5ab	-	0.128a	4.68b
Windrowed slash	1.42ab	0.10b	18.0b	-	71.3a	8.1a	-	0.141a	4.89ab
Standard errors	+/-0.09	+/-0.04	+/-8.5	-	+/-12.4	+/-1.5	-	+/-0.032	+/-0.30
30 cm depth									
p-values, 2, df	0.014	-	0.001	<0.001	0.092	0.007	0.023	0.002	0.020
Mulch	1.46a	-	55.3a	20.8b	113.6a	4.0b	0.29b	0.094b	5.31a
Spread slash	1.23b	-	29.1b	29.7a	151.3a	9.3a	0.38ab	0.203a	4.53a
Windrowed slash	1.23ab	-	24.7b	34.8a	188.8a	7.5ab	0.42a	0.170a	4.58a
Standard errors	+/-0.13	-	+/-10.8	+/-6.8	+/-35.4	+/-0.5	+/-0.06	+/-0.055	+/-0.44

Table 3.13. Means and one-way ANOVA results for comparisons of response to deep (n=18) versus shallow (n=18) mulch treatments in planted spruce height, DBH and survival, and two-way ANOVA including planting treatment results for regenerating aspen density, DBH, and height; two-way ANOVA for response of other dominant regenerating tree species density on northern Alberta boreal well sites. Differences among least square means are indicated by letters following the mean values.

	Planted Spruce			
Means and ANOVA	Height (cm)	DBH (cm)	Survival (%)	MANOVA, 6 df
Mulch depth treatment				
p-values, 8 df	0.142	0.129	0.347	0.387
Deep	217.41	16.88	77.8	
Shallow	126.86	4.80	74.1	
Standard errors	+/-27.36	+/-3.51	+/-0.04	

	Regenerating Aspen			
Means and ANOVA	Density (stems m^{-2})	DBH Class	Height Class	MANOVA, 3 df
Mulch depth treatment				
p-values, 24, 19, 18 df	0.063	0.185	0.061	0.129
Deep	0.51	2.64	3.18	
Shallow	0.85	3.19	3.69	
Standard errors	+/-0.09	+/-0.24	+/-0.14	
Planting treatment				
p-values, 24, 19, 18 df	0.448	0.376	0.391	0.830
Planted	0.61	2.71	3.29	
Non-planted	0.75	3.07	3.54	
Standard errors	+/-0.09	+/-0.25	+/-0.14	
Mulch depth * Planting				
p-values, 24, 19, 18 df	0.136	0.242	0.290	0.162

Means and ANOVA Mulch depth treatment	Birch (stems m^{-2})	Poplar (stems m^{-2})	Spruce (stems m^{-2})	Total Density (stems m^{-2})
p-values, 24, 19, 18 df	0.130	0.027	0.250	0.259
Deep	1.01	0.29	0.22	2.26
Shallow	1.58	0.01	0.32	2.89
Standard errors	+/-0.17	+/-0.14	+/-0.05	+/-0.31
Planting treatment				
p-values, 24, 19, 18 df	0.430	0.016	0.142	0.059
Planted	0.61	0.31	0.33	3.11
Non-planted	0.75	0.00	0.21	2.04
Standard errors	+/-0.07	+/-0.15	+/-0.06	+/-0.53
Mulch depth * Planting				
p-values, 24, 19, 18 df	0.118	0.027	0.408	0.464
Deep planted	0.58	0.58a	0.25	3.00
Deep non-planted	0.44	0.03b	0.19	1.53
Shallow planted	0.64	0.00b	0.42	3.22
Shallow non-planted	1.06	0.00b	0.22	2.56
Standard errors	+/-0.14	+/-0.14	+/-0.03	+/-0.20

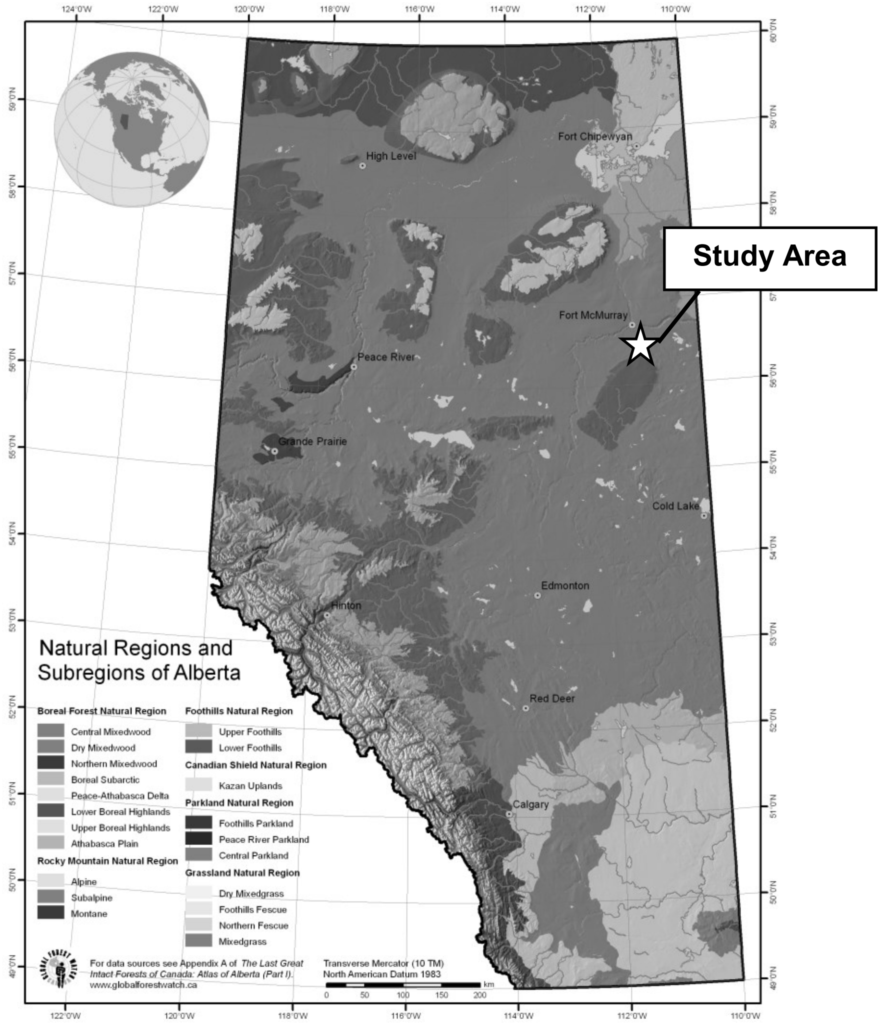

Figure 3.1. The natural subregions of Alberta, adapted from Global Forest Watch Canada (2005).

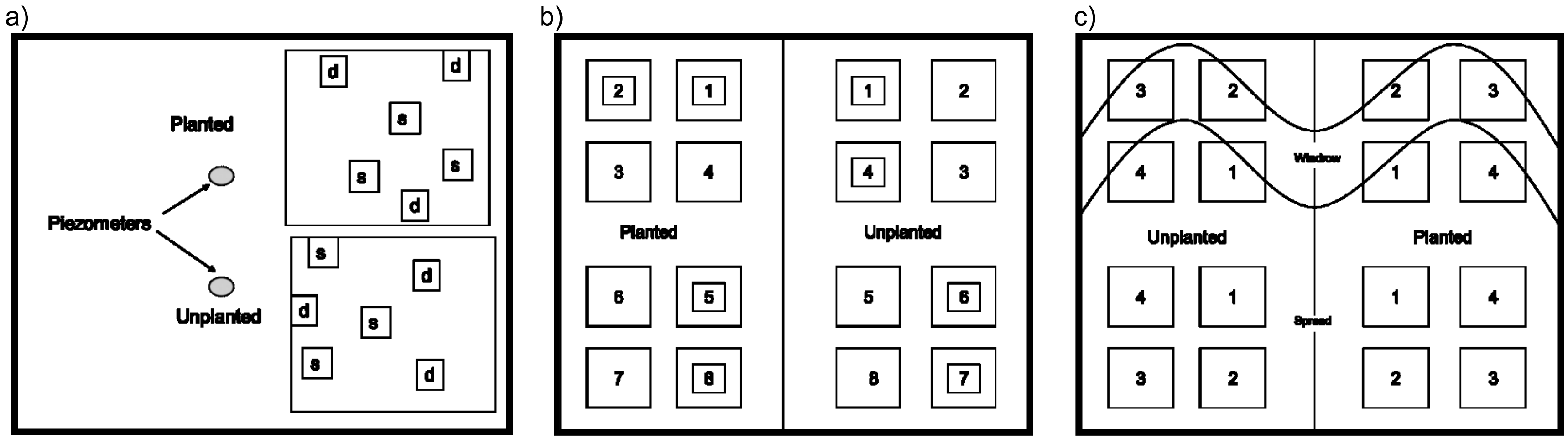

Figure 3.2. Site schematic for a) shallow [s] and deep [d] mulch plots within mulch depth treatment sites; b) a site with one woody debris treatment, further split into planted and non-planted treatments; c) a site with two woody debris treatments and planted and non-planted treatments.

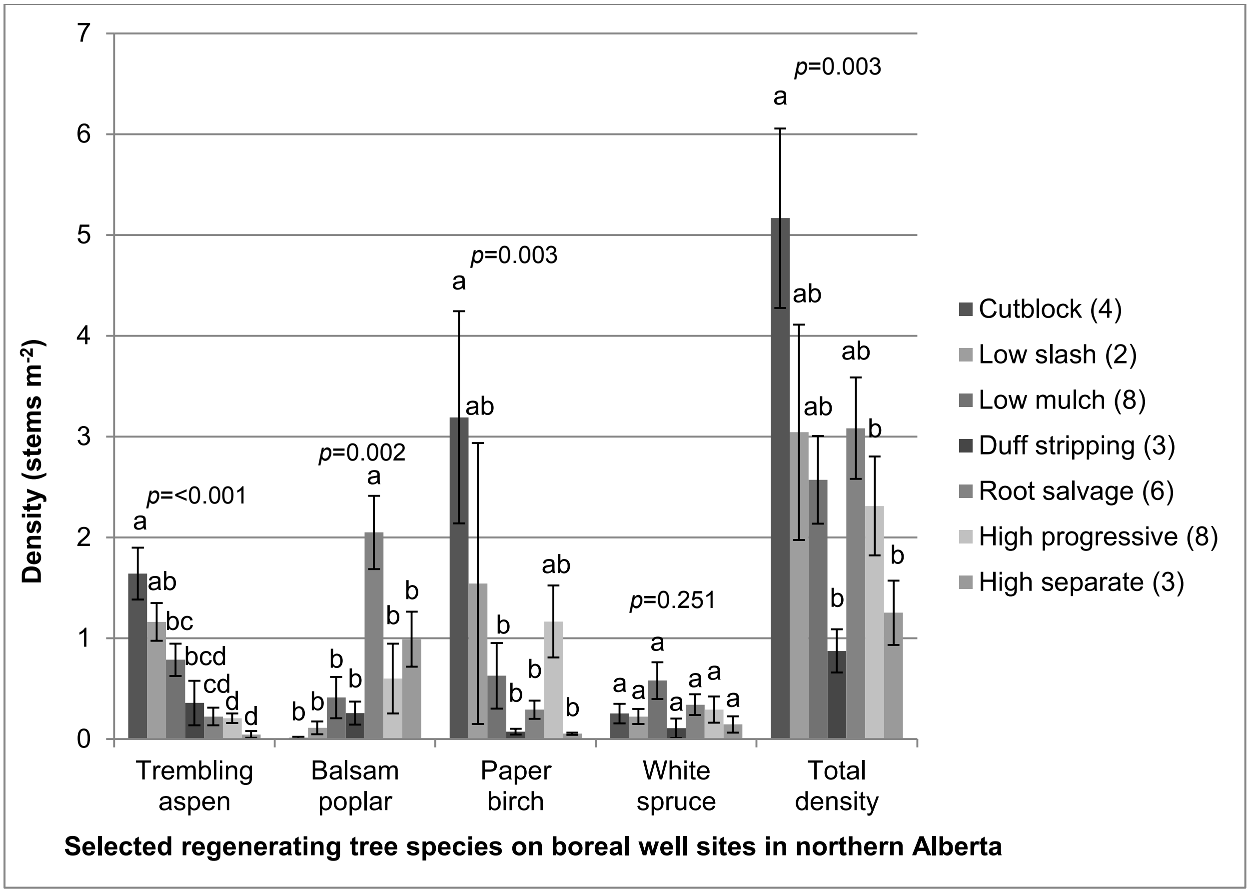

Figure 3.3. Comparative regeneration density and total density (stems m^{-2}) of selected tree species between soil treatment groups on northern Alberta boreal well sites. Above bars, p-values indicate significance of variation between groups based upon ANOVA. Lettering above bars indicate differences between means based upon LSD test results. Numbers next to treatment group labels in legend indicate sample size (n).

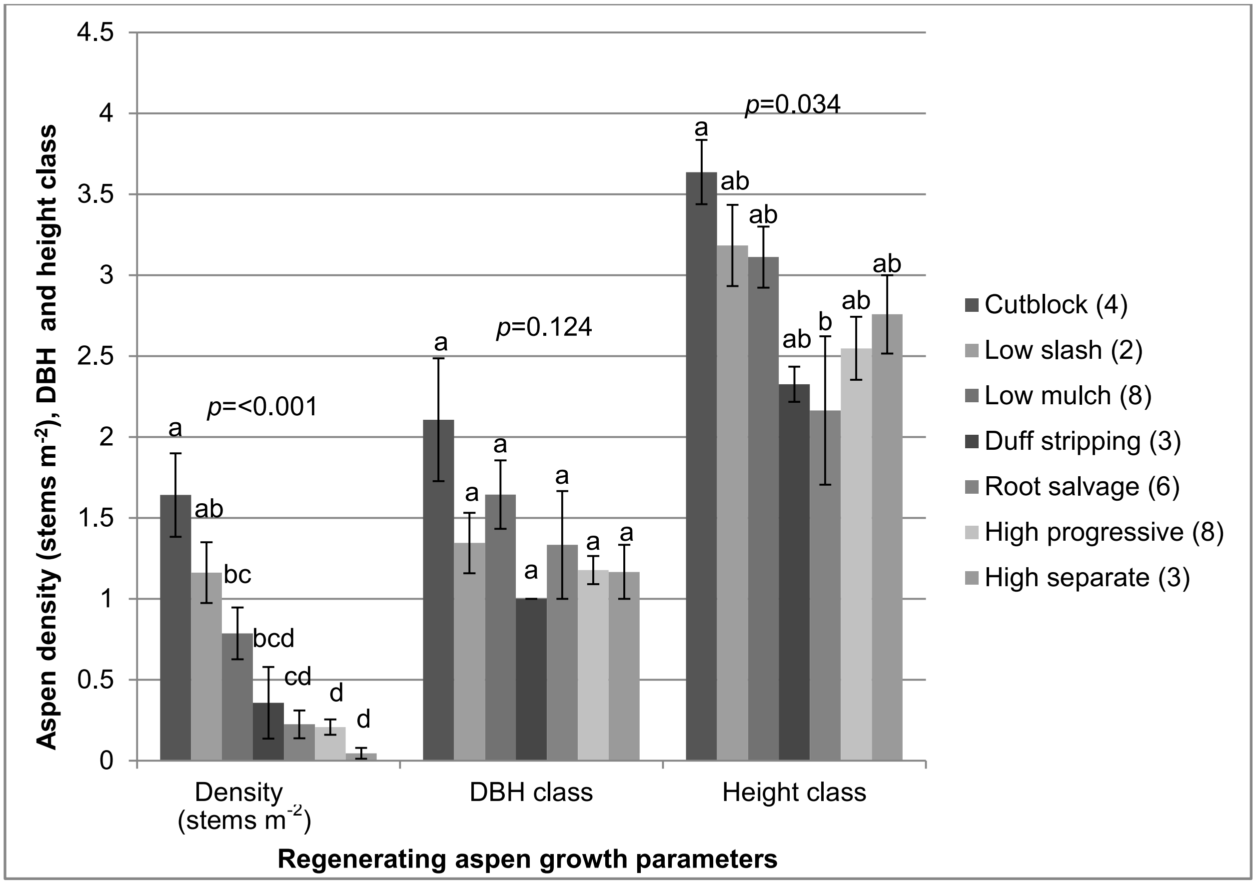

Figure 3.4. Comparative regenerating aspen performance ten years after harvest or oil sands exploratory disturbance on northern Alberta boreal well sites based upon ANOVA. Values above bars indicate p-values. Lettering above bars indicate differences between means based upon LSD test results. Numbers in legend indicate number of treatment sites (n).

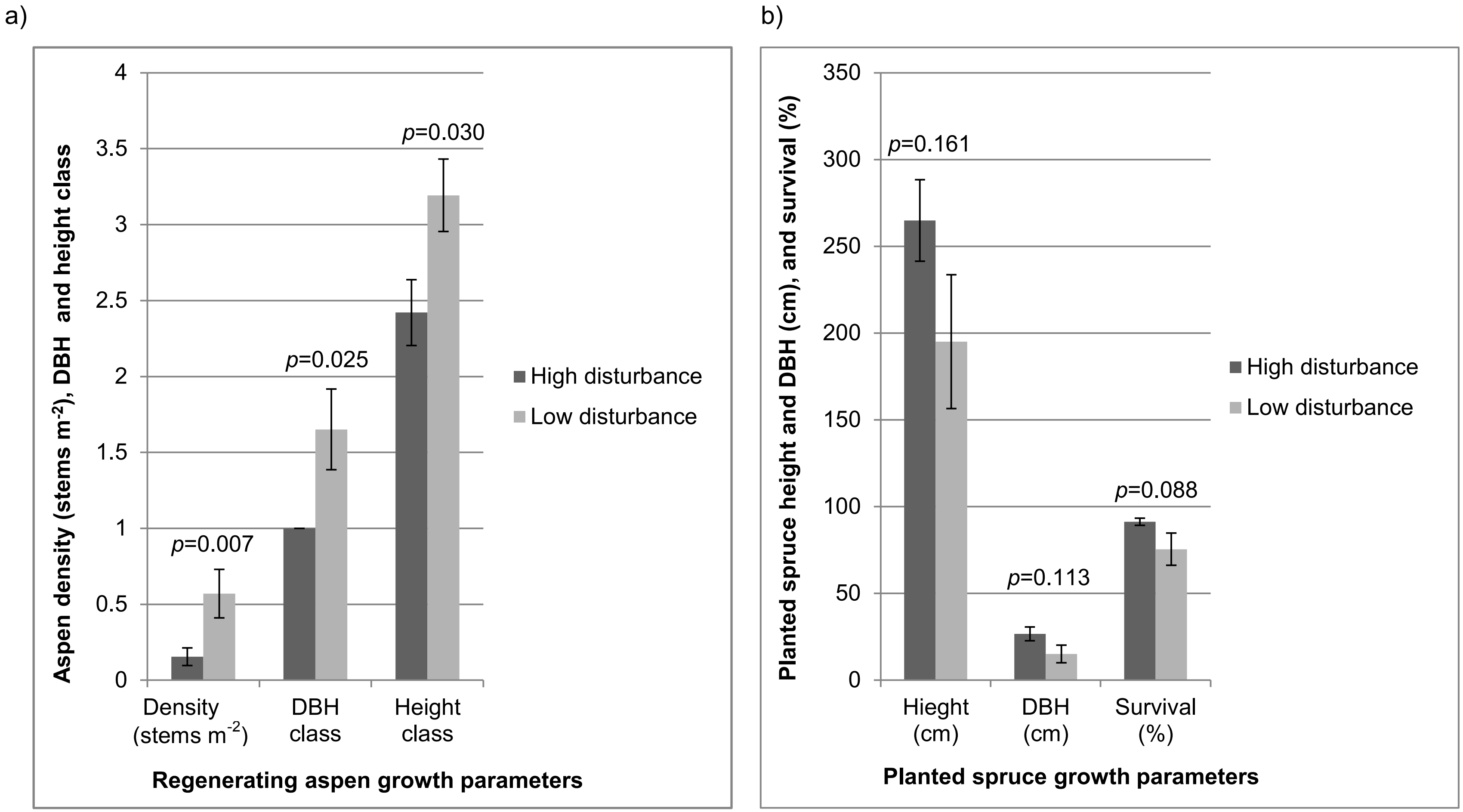

Figure 3.5. Comparative performance of a) regenerating aspen and b) planted spruce between high (n=5) and low (n=5) disturbance treatments on northern Alberta boreal well sites based on ANOVA. Values above pairwise bars indicate p-values.

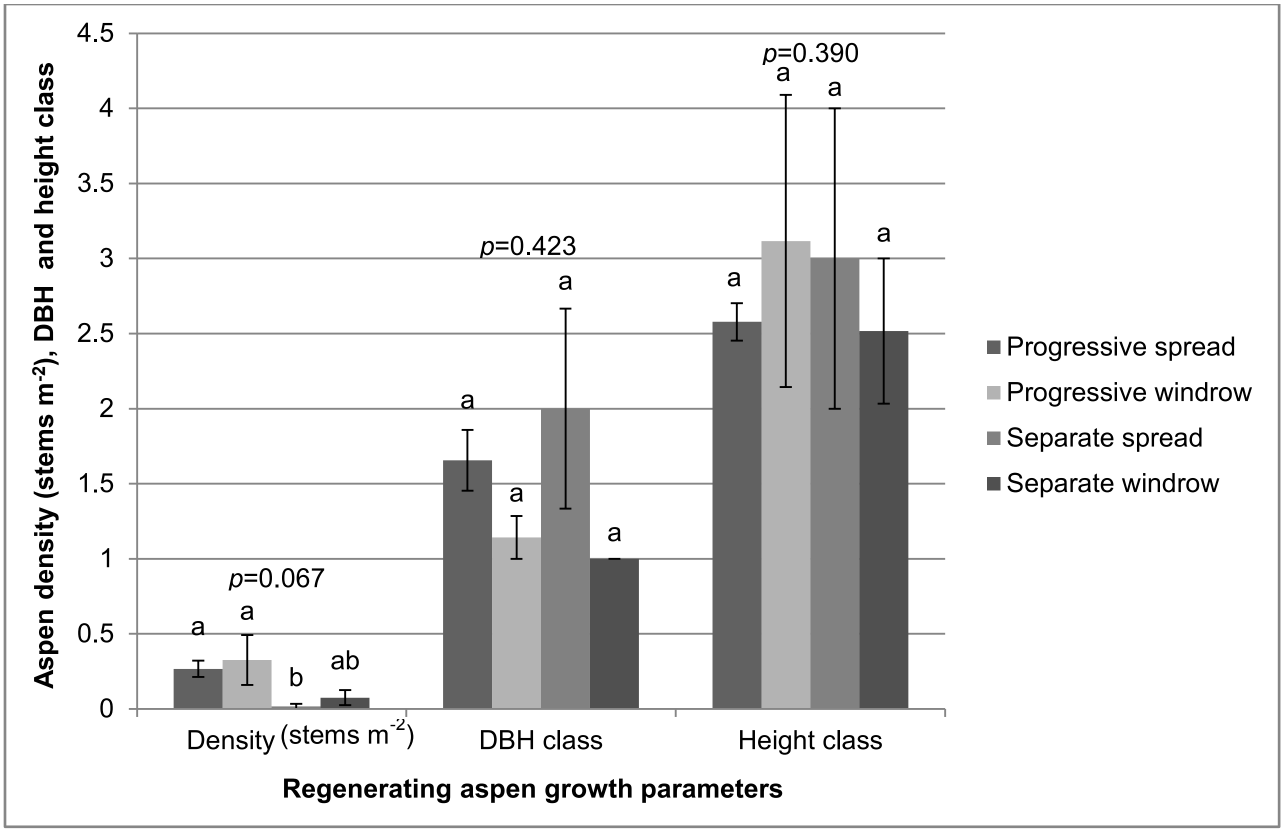

Figure 3.6. Comparative regenerating aspen performance within progressive (n=3) and separate (n=3) soil pile treatments treated with spread or windrowed slash on northern Alberta boreal well sites based on ANOVA. Values above pairwise bars indicate p-values. Lettering above bars indicates differences between means based upon LSD test results.

CHAPTER IV: SYNTHESIS AND FUTURE RESEARCH

1. RESEARCH SUMMARY

1.1. Overview

Thirty-three research sites were established on oil sands exploration well sites in boreal forest near Anzac, Alberta between 2004 and 2006 and reclaimed during winter using different soil handling and woody debris management methods. Survival and growth of planted spruce were compared between treatments. Soil chemical and physical properties were compared between treatments and and forest controls. Naturally regenerating trees and plant communities were compared between treatments, forest controls and cutblocks harvested in 2004.

Thirteen well sites were constructed with low disturbance (iced-in) with spreading and windrowing of whole slash and mulch application at depths ≤ 5 cm and ≥ 10 cm and planting treatments. Eleven study sites were constructed and reclaimed using conventional soil stripping, storage and replacement, followed by application of spread or windrowed whole slash with soil storage (piling) methods, woody debris application and planting treatments.

Two construction methods hypothesized to reduce impacts on plant propagules during site levelling were compared with conventional methods. Duff stripping, removing only the surface (LFH) layer was applied at three sites; surface soils and whole slash were evenly spread at reclamation and planting treatments applied. Root salvage employed excavation at a depth below the main aspen rooting zone; slash was evenly spread after soil replacement, and no planting treatments were applied.

Except for six root salvage sites, whose excavation method was designed to examine natural tree regeneration, all sites were planted in early summer following reclamation with 150 to 200 trees on a randomly selected half of the well site, creating planted and non-planted treatments. In 2004, alternating rows of *Populus tremuloides* Michx (trembling aspen), *Populus balsamifera* L (balsam poplar) and *Picea glauca* (Moench) Voss (white spruce) were planted. Sites reclaimed in 2005 and 2006 were planted with the same species and *Betula papyrifera* Marshall (paper birch) between rows of aspen and spruce. Trees were planted at 2 m grid spacing, for an equivalent planting density of 3,300 trees per ha.

The project, Removing the Wellsite Footprint, was initiated in 2003 to address potential inconsistencies with reclamation guidelines for the oil and gas industry that have persisted in the green (forested) zone of Alberta. The research was designed to identify factors that contribute to poor ecological recovery on upland boreal oil sands exploration sites and assess whether they could be mitigated during construction and/or reclamation.

After initial assessments, Osko and Glasgow in 2010 made recommendations for best practices for well site construction and reclamation on upland boreal well sites. Our goal 10 years post reclamation was to assess treatment effects on successional development of sites, and planted spruce in the longer term. For this study, success is defined as identifying factors that contribute to greater (and more rapid) vegetation successional development convergent with the surrounding forest, including factors that promote regeneration of native plant communities.

Vegetative regrowth properties were assessed, including structure, species richness and diversity and similarity to forest controls nine or ten years after reclamation. Ground cover components, including bare soil, litter, woody debris, moss and lichen, were estimated (total of 100 %). All naturally regenerating trees in quadrats were counted and average height and diameter at breast height were recorded as class variables. Cutblocks established in 2004 were used as a proxy to natural disturbance to compare regenerating plant communities within treatments. Cutblocks and forest controls were assessed similar to treatment communities.

Planted spruce were located; presence or absence (survival) and measurements of height and DBH were made. Naturally regenerating plant communities and tree densities were compared between pre-determined treatment groups and treatments and cutblocks. Plant communities were compared to forest controls and planted spruce performance was compared between treatments. Where differences in aspen regeneration or planted spruce performance were detected between treatments, comparisons of soil physical and chemical attributes were made.

1.2. Soil Disturbance, Soil Storage, Woody Debris And Planting Treatment Impacts On Plant Community Development

Disturbance intensity of oil sands exploration treatments and treatment combinations in this study can be characterized and categorized by their degree of similarity in species composition to forested controls and physical similarity of vegetative regrowth to cutblocks, including development of the tree canopy relative to the grass and shrub understory. The parameters are dependent on degree of alteration to site conditions and propagule pool of each disturbance.

Low disturbance methods that use whole slash as a reclamation tool resulted in a relatively high tree cover and greatest likelihood of prompt return to boreal forest communities. Leaving aspen roots intact through minimal soil disturbance (without removal and handling) is a key factor in site recovery. Proportional availability of propagules for regrowth likely remained intact under minimal disturbance practices. Shrub growth on low disturbance sites was likely stimulated by vegetation damage and removal, but did not proportionally increase relative to other vegetation groups via root fragmentation and propagule spread. With mulch left after reclamation, low disturbance sites showed the benefit of leaving aspen roots intact with greater tree cover and a higher tree to grass shrub ratio than high disturbance sites. However, mulch resulted in forb suppression, altering the plant community and providing more space for non-native species.

Duff stripping resulted in greatest alteration of propagule representation in vegetation groups. Although leaving aspen roots intact resulted in higher aspen cover than conventional stripping, tree cover was not greater than with high disturbance methods. Tree seeds likely desiccated and germinants may have perished in loosened LFH or were suppressed by a high grass cover.

With mineral soil disturbance, fragmentation and dispersal of *Rubus idaeus* and *Calamagrostis canadensis* roots may have occurred, resulting in increased propagules for regeneration. Tree and dicotyledon seeds normally at the soil surface become mixed into the soil and buried seeds emerge. A proportional change in propagule numbers of individual species, and propagules of different vegetation groups, likely occurred with conventional stripping, and further alteration due to desiccation in separate soil piles. Increasing soil disturbance reduces structural complexity of regenerating plant communities and plant species diversity. Root salvage was likely more similar to controls due to retention of large soil aggregates, and intact roots and seeds within.

Although it seems uncertain whether any treatment involving high soil disturbance can consistently become fully reforested in the absence of intervention or further disturbance, root salvage seems to be a preferable treatment. Similar to duff stripping, root salvage did not increase tree cover relative to conventional stripping, but did retain higher species richness and structural diversity. Root salvage either did not result in the same degree of plant community change, or recovered from disturbance more quickly.

Windrowing improved canopy cover on high disturbance sites, providing more suitable habitat for *Betula papyrifera* and *Picea glauca*, and in the separate soil pile treatment, potentially mitigating effects of desiccation of propagules resulting in greater aspen cover. Forest recovery was aided by planting, which inherently increases tree density. Where disturbance intensity altered plant community assemblages to favour competitive grass and/or shrubs, planting trees reduced their cover, and increased species richness and/or diversity in high and low soil disturbance treatments.

1.3. Soil Disturbance, Soil Storage And Woody Debris Treatment Impacts On Naturally Regenerating Trees, Planted Spruce And Soil Chemical And Physical Properties

Little difference was found in survival and growth of planted spruce between treatments, although spruce responded more favourably where soil mixing occurred. Tree species composition on regenerating oil sands exploration sites is inconsistent with regeneration on comparably disturbed areas associated with forest harvest (clear cutting).

Aspen regeneration decreased with increasing soil disturbance. Low disturbance methods are clearly beneficial to aspen regeneration. Aspen in the low disturbance treatment regenerated at relatively higher densities due to intact root systems. In contrast, the high disturbance treatment impacted aspen by fragmentation of root systems, removal of clonal growth support and displacement of fragments. Disturbance intensity increasingly favours more competitive species (poplar), simultaneously reducing aspen presence on the landscape, and reducing sucker survival. Aspen canopy gaps may persist through several natural disturbances before successful reestablishment of clonal root systems.

More severe disturbance of forest areas may have reduced tree seeds and/or propagules which likely led to low tree regeneration densities insufficient for successful forest reestablishment. Exposure of soils to the atmosphere and low temperatures may reduce soil fauna and bacteria. Soil productivity can be hampered by soil microbial and invertebrate population losses, directly affecting re-establishment of trees and long term growth and survival of planted spruce and regenerating aspen. Soils with reduced productivity may have led to low canopy cover uncharacteristic of early successional boreal forest. Root salvage provides similar protection of aspen roots and soil biota as conventional stripping with progressive piling, which reduces soil surface area exposure during storage. Unlike conventional stripping with progressive piling, root salvage may better promote mixedwood development.

Wood treatments were influential in tree regeneration. Mulch can protect soils and aspen roots from compaction, but may hinder regeneration density with increasing mulch depth. Mulch applied over sandy soil (70 % sand) was deleterious to planted spruce survival and growth. Although mulch can retain subsurface water, the reflective heat it produces in absence of sufficient water in well drained areas may increase transpiration stress in planted spruce to impact its long term survival. It may provide a suitable germination substrate for spruce, whose numbers may increase from cones or seeds in the mulch. However, mulch reduces the ability of many other plant species to either germinate or survive. Seeds and propagules may respond better to non-continuous woody debris surface cover.

Retention and redistribution of whole slash after low disturbance site abandonment, rather than mulch may result in better plant community regrowth, more similar to post harvest conditions. Windrowing as an alternative to spreading woody debris reduces the area of soil surface in direct contact with woody material. This may encourage soil warming and stimulate aspen suckering. Warmer soils may stimulate microbial recovery and increase soil productivity. Non-vascular plants may be beneficial to aspen regeneration by reducing germination space for competing vegetation. These combined effects may benefit aspen recovery after high soil disturbance and damage to root systems.

1.4. Differences In Findings From 2010

Only results discussed in Osko and Glasgow's 2010 recommendations for construction and reclamation of well sites on upland forests are discussed here. We cannot follow up on all findings, as confounding factors affected our ability to assess planted birch, aspen and poplar.

Planted spruce growth remained better on high than low disturbance sites, although differences became less apparent over time. Regenerating aspen densities remained greater on low disturbance sites. Low disturbance sites had approximately 10,000 to 15,000 aspen trees per ha at year 5 and 5,700 trees per ha in year ten on the same sites, which is not unusual as a natural result of self thinning. Estimated total density of other tree species was similar between low and high disturbance treatments at year five, approximately 3,000 trees per ha. Currently, there are 16,600 trees per ha other than aspen on low disturbance sites, and 20,100 on high disturbance sites, most is birch for both treatments. Spruce densities are 3,900 and 3,100 trees per ha on low and high disturbance sites, respectively.

Within the high disturbance treatment, regenerating tree densities were previously higher on sites where soils had been stored separately rather than progressively. This changed over time, such that total density is now greater in the progressive soil pile treatment (25,500 versus 12,500 trees per ha). Both naturally regenerating aspen and birch densities at year nine were quite low as a result of separate soil piling, but spruce densities did not differ. Similar to earlier results, planted spruce survival was not affected by soil piling method. Spruce growth was previously negatively affected by progressive soil piling, but no longer. At year nine, planted spruce performance was similar between soil piling treatments, but negatively affected by spreading rather than windrowing whole slash in the separate soil pile treatment. Vegetation may have initially flourished in soils that had been piled separately due to high nitrogen content, but possibly languished over time due to low plant diversity and soil productivity.

Shrub diversity and total tree density were previously greater on root salvage sites than conventionally stripped sites. More recently, species richness (including all cover types) was greater on root salvage sites, but total tree density did not differ from high disturbance sites. Aspen cover and poplar density were greater in the root salvage treatment.

Poplar and birch densities were previously greater in low disturbance treatment sites where whole slash rather than mulch was applied. While birch density is still lower, poplar densities are greater on mulched sites than whole slash treatments, and even greater in deep mulch, although this may be influenced by planting. Spruce density was higher on mulched sites, but overall total tree densities did not differ. At year five, there were no differences between wood treatments in herbaceous cover or diversity, but there were differences in cover over the long term. Forb and total cover were lower on mulched sites, while litter was higher than on whole slash sites. Deep mulch previously had lower tree densities than shallow mulch. That still occurs, and tree cover relative to grass and shrub cover is greater in shallow mulch. Total cover and species richness no longer differ between mulch depth treatments, but non-native diversity is greater in the deep mulch treatment. This suggests that low disturbance mulched sites become incrementally less productive over time, an effect with increases with mulch depth, relative to sites with whole slash.

As previously observed, planted poplar growth was quite robust relative to the other species planted, despite the presence of competitive herbaceous vegetation. This effect was observed on many sites including those impacted by increased water content due to disturbance.

2. IMPLICATIONS FOR ALBERTA OIL SANDS EXPLORATION WELL SITE MANAGEMENT, REFORESTATION AND RECLAMATION PRACTICES

Many sites had simultaneous reforestation with planted spruce and regenerating aspen, but there is difficulty associated with managing soil disturbance and woody debris for both species. Although low disturbance methods are cost effective for industry and the environment, high disturbance methods may be necessary for site construction. Early growth of planted spruce is augmented and regenerating aspen impacted by soil disturbance. This is a concern in Alberta boreal forest where managing for mixedwoods is a high priority. Where sites are located in a

Forest Management Agreement area, if high disturbance methods are used, tree volumes may not produce outcomes that meet projected forest harvest goals. Low disturbance methods may more appropriately meet ecological goals, and maintain healthy aspen stands for future harvest. High disturbance methods may be preferable where spruce plantings are required to fulfill anticipated softwood demand, but these may come at the ecological cost of distortion of native plant communities. Therefore, delineation of clear end land use objectives prior to disturbance is crucial for management to appropriately select construction and reclamation practices to meet those goals. If soil disturbance is deemed necessary, minimizing soil surface area exposure during storage will likely protect plant propagules and soil biota.

Increased disturbance intensity, including soil removal, handling and associated debris treatment, reduces the likelihood of rapid and efficient reforestation after oil sands exploration disturbance. For upland boreal well sites to more consistently return to forested communities, low disturbance methods should be used, preferably with an ice-in well pad (not including mulch), leaving whole slash for distribution upon reclamation. If mulching is necessary, site managers should ensure that the mulch layer remains on site in as thin a layer as possible, and consider leaving ground patches free of mulch to allow propagules that require direct sun and warmer conditions to regenerate.

Treatment applications are commonly determined by construction feasibility based on local topographic conditions and residual woody debris volume. Low disturbance methods are generally lower cost than excavation, and can be implemented on sites of moderate topographic variation, thereby reducing exploration costs and impacts to aspen root systems. Performing construction without leaving a mulch footprint could further reduce disturbance and produce regeneration densities similar to post harvest scenarios (Bachman et al 2015).

Mulch use should be avoided in well drained soils if spruce planting is part of the reclamation plan. Whole slash is now commonly redistributed as part of reclamation. Variation in woody debris distribution such that some areas are evenly spread and others windrowed or somewhat piled, with bare areas between, may encourage establishment of non-vascular plant species, and positively influence soil productivity, forest recovery and aspen regeneration density. It would be worth examining effects of this practice over a large geographic area on more sites.

Where excavation is unavoidable, a thorough site assessment should be conducted to determine potential impacts of construction and woody material management methods. Soil storage methods should be applied to limit soil surface area exposure as this may impact soil biota and plant propagules. This could impact post reclamation soil and vegetation rehabilitation; without which sites are at risk of not achieving adequate canopy capture and returning to productive mixedwood forest.

Selecting sites with observable populations of *Calamagrostis canadensis* and/or *Rubus idaeus* increases the risk of herbaceous regrowth resulting in grass or shrub meadow post reclamation. Methods should be used to preserve natural presence of plant species in the seed and propagule bank. Where possible, duff and upper mineral layers should be protected, which may prevent potential losses of seeds and propagules to desiccation. Although separate soil piling may reduce mixing of soil layers, any benefit thereof is likely negligible due to damage to the regeneration pool, and should be avoided. Separate soil piling requires a larger area than single progressive piles and therefore necessitates a larger lease size, leading to more disturbance than necessary. Overall, root salvage may be preferable, as it resulted in less change to local habitat, or faster recovery from disturbance, than other high disturbance methods.

Tree planting provided a range of benefits that contributed to faster forest recovery and increased structural and species diversity. Benefits of planting were apparent on high and low disturbance sites, and should be a standard practice after oil sands exploration disturbance. Using low disturbance methods as far as possible should be standard practice as well. They not only reduce the cost of site construction, but reduce the long-term liability associated with management of reclaimed and recovering well sites.

3. FUTURE RESEARCH

Low disturbance methods are clearly preferable for forest recovery. Mulch may be a key component in protection of the forest floor in areas where compaction may result from construction operations. Research should be conducted to determine how mulch volume may be minimized, and what methods may be used to expose the forest floor after mulch pad use without disturbance of duff and upper mineral layers.

Further research is needed to understand effects of soil excavation and storage on soil biota and soil physical and chemical properties. There has been little investigation into how soils are altered by these activities on oil sands exploration sites. Stockpiling likely affects soil productivity and plant health. Plant seeds and propagules are likely affected by different stockpiling methods, with some species negatively affected, and others promoted. All these factors affect subsequent regeneration and successional development. Root salvage appeared to conserve both plant propagules and soil biota. The second pass in root salvage was piled separately, but may have been of better use as insulation over top the first pass as in progressive piling. This may have improved aspen regeneration density in root salvage relative to the progressively piled two-pass stripping treatment.

Windrowing slash assists in forest recovery where soils have been excavated. Investigations should determine if it is the bare space between windrows or the structural variation of windrows that encourages tree development. Windrowing is currently not allowed on oil sands exploration sites in Alberta due to their potential fire wicking hazard. However, considering the small size of oil sands exploration sites, windrows would be unlikely to contribute to fire spread, which would quickly travel around or through an oil sands exploration site anyway. This hazard is more appropriately identified for cutblock areas which are much larger in size. It is likely that windrows are not permitted on oil sands exploration sites so that regulations are consistent between forestry and oil and gas operations, and therefore simpler to apply. However, the benefits of windrowing may outweigh this misidentified hazard.

Some study sites were likely burned in spring 2016. This may be a valuable opportunity to assess how fire resets vegetation succession on oil sands exploration sites, especially where trees may have been outcompeted by grass or shrubs.

BIBLIOGRAPHY

Abrahamson, I. 2015. Picea glauca, white spruce. In: Fire effects information system, United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). On line at http://www.fs.fed.us/database/feis/plants/tree/picgla/all.html. Accessed 2 December 2016.

Alberta Agriculture and Forestry. 2015. Alberta rangelands in range and pasture management. Alberta Agriculture and Forestry. On line at http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag2111. Accessed 20 June 2016.

Alberta Geological Survey. 2013. Alberta Oil Sands. Onn line at http://www.ags.gov.ab.ca/energy/oilsands/index.html. Accessed 12 September 2014.

Alberta Transportation. 2013. Alberta transportation guide to reclaiming borrow excavations. On line at http://www.transportation.alberta.ca/Content/DocType245/Production/borrowguide.pdf. Accessed 8 December 2014.

Amaranthus, MP, DS Parrish and DA Perry. 1989. Decaying logs as moisture reservoirs after drought and wildfire. Pp 191-194. In: EB Alexander (ed). Proceedings of Watershed 89 a Conference on the Stewardship of Soil, Air, and Water Resources. United States Department of Agriculture, Forest Service Alaska Region. Juneau Alaska.

Archibold, OW, C Acton and EA Ripley. 2000. Effect of site preparation on soil properties and vegetation cover and the growth and survival of white spruce *(Picea glauca)* seedlings, in Saskatchewan. Forest Ecology and Management 131:127-141.

Ashworth, J and K Mrazek. 1995. Modified Kelowna test for available phosphorus and potassium in soil. Communications in Soil Science and Plant Analysis 26:731-739.

Bachmann, S, VJ Lieffers and SM Ländhausser. 2015. Forest floor protection during drilling pad construction promotes resprouting of aspen. Ecological Engineering 75:9-15.

Beach, EW and CB Halpern. 2001. Controls on conifer regeneration in managed riparian forests: effects of seed source, substrate, and vegetation. Canadian Journal of Forest Research 31:471-482.

Beckingham, JD. 1993. Ecosystem associations of Northern Alberta. Department of Environmental Protection, Alberta Forest Service. Edmonton Alberta.

Beckingham, JD and JH Archibald, 1996. Field guide to ecosites of northern Alberta. Natural Resources Canada, Canadian Forest Service, Northwest Region, Northern Forestry Centre. Edmonton Alberta. Special Report 5.

Berger, AL, KJ Puettmann and GE Host. 2004. Harvesting impacts on soil and understory vegetation: the influence of season of harvest and within-site disturbance patterns on clear-cut aspen stands in Minnesota. Canadian Journal of Forest Research 34:2159-2168.

Bergeron, Y, HYH Chen, NC Kenkel, AL Leduc and SE Macdonald. 2014. Boreal mixedwood stand dynamics: ecological processes underlying multiple pathways. The Forestry Chronicle 90:202-213.

Blake, GR. 1965. Bulk density. Pages 374-390 In: CA Black (ed). In: Methods of soil analysis, part 1. American Society of Agronomy. Monograph 9. Madison Wisconsin.

Boateng, JO, JL Heineman, J McClarnon and L Bedford. 2006. Twenty year responses of white spruce to mechanical site preparation and early chemical release in boreal region of northeastern British Columbia. Canadian Journal of Forest Research 36:2386-2399.

Bonan, GB and HH Shugart. 1989. Environmental factors and ecological processes in boreal forests. Annual Review of Ecology and Systematics 20:1-28.

Boyle, TJB. 1992. Biodiversity of Canadian forests - current status and future challenges. Forestry Chronicle 68:444-453.

Brady, NC and RR Weil. 2010. Elements of the nature and properties of soils. Prentice Hall. New Jersey United States of America. 614 pp.
Brandner, TA, RO Pererson and KL Risenhoover. 1990. Balsam fir on Isle Royale – effects of moose herbivory and population density. Ecology 71:155-164.
Brandt, JP, MP Flannigan, DG Maynard, ID Thompson and WJA Volney. 2013. An introduction to Canada's boreal zone: ecosystem processes, health, sustainability, and environmental issues. Environmental Review 21:207-226.
Brown, RL and MA Naeth 2014. Woody debris amendment enhances reclamation after oil sands mining in Alberta, Canada. Restoration Ecology 22:40-48.
Burton, PJ, C Messier, DW Smith and WL Adamowicz (eds). 2003. Towards sustainable management of boreal forest. NRC Research Press. Ottawa Ontario Canada. 1039 pp.
Buck, JR and SB St Clair. 2012. Aspen increase soil moisture, nutrients, organic matter and respiration in Rocky Mountain forest communities. PLoS One 7: article number e52369.
Burns, RM and BH Honkala. 1990. Silvics of North America, volume 2, Hardwoods. Agricultural handbook Number 654. United States Department of Agriculture and Forestry Service. Washington DC. 877 pp.
Campbell, DJ and JK Henshall (eds). 1991. Bulk Density. In: Soil and environmental analysis. Marcel Dekker. New York United States. Pp.329-366.
Canadian Association of Petroleum Producers(CAPP). 2014. What are oil sands? On line at http://www.capp.ca/CANADAINDUSTRY/OILSANDS/ENERGY-ECONOMY/Pages/what-are-oilsands.aspx. Accessed 3 October 2014.
Christy, EJ and RN Mack. 1984. Variation in demography of juvenile *Tsuga heterophyla* across the substratum mosaic. Journal of Ecology 72:75-91.
Cole, E, A Youngblood and M Newton. 2003. Effects of competing vegetation on juvenile white spruce (*Picea glauca* (Moench) Voss) growth in Alaska. Annals of Forest Science 60:573-583.
Coleman MD, RE Dickson and JG Isebrands. 1998. Growth and physiology of aspen supplied with different fertilizer addition rates. Physiologia Plantarum 103:513-526.
Conlin, TSS. 2001. In-woods chipping: possible evidence for allelochemical interaction of leachate generated from trembling aspen (*Populus tremuloides* Michx.) bark and wood waste. Forestry Chronicle 77:345-349.
Cooke, BJ and J Roland. 2007. Trembling aspen responses to drought and defoliation by forest tent caterpillar and reconstruction of recent outbreaks in Ontario. Canadian Journal of Forest Research 37:1586-1598.
Corns, IGW. 1987. Compaction by forestry equipment and effects on coniferous seedling growth on four soils in Alberta foothills. Canadian Journal of Forest Research 18:75-84.
Corns, IGW and DG Maynard. 1998. Effects of soil compaction and chipped aspen residue on aspen regeneration and soil nutrients. Canadian Journal of Soil Science 78:85-92.
Curzon, MT, AW D'Amato and BJ Palik. 2014. Harvest residue removal and soil compaction impact forest productivity and recovery: potential implications for bioenergy harvests. Forest Ecology and Management 329:99-107.
Day, RJ. 1972. Stand structure, succession and use of southern Alberta's Rocky Mountain Forest. Ecology 53:472-478.
De Cáceres, M. 2013. How to use the indicspecies package (ver 1.7.1). On line at https://cran.r-project.org/web/packages/indicspecies/vignettes/indicspeciesTutorial.pdf. Accessed 5 August 2016.
De Cáceres, M and F Jansen. 2015. Package 'indicspecies'; relationship between species and groups of sites. On line at https://cran.r-project.org/web/packages/indicspecies/indic species.pdf. Accessed 5 August 2016.

De Cáceres, M, P Legendre and M Moretti. 2010. Improving indicator species analysis by combining groups of sites. Oikos 119:1674-1684.

De Grandpré, L, D Gagnon and GD Bergeron. 1993. Changes in the understory of Canadian southern boreal forest after fire. Journal of Vegetation Science 4:803-810.

Duan, M, J House and SX Chang. 2015. Limiting factors for lodgepole pine (*Pinus contorta*) and white spruce (*Picea glauca*) growth differ in some reconstructed sites in the Athabasca oil sands region. Ecological Engineering 75:323-331.

Dufrêne, M and P Legendre. 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecological Monographs 67:345-366.

Eis, S. 1967. Establishment and early development of white spruce in the interior of British Columbia. Forestry Chronicle 43:174-177.

Environment and Sustainable Resource Development (ESRD). 2009. Management of wood chips on public land. Lands Division, Land Management Branch, Petroleum Land Use and Reclamation Section, Government of Alberta. Industry Directive Number: ID 2009-01. Edmonton Alberta. 2 pp.

Environment and Sustainable Resource Development (ESRD) 2013. 2010 Reclamation criteria for wellsites and associated facilities for forested lands (Updated July 2013). Edmonton Alberta. 81 pp.

Forest Research Advisory Council of Canada. 1994. Forest research priorities in Canada, 1993. Forestry Chronicle 70:84-87.

Franklin, CMA and KA Harper. 2016. Moose browsing, understorey structure and plant species composition across spruce budworm-induced forest edges. Journal of Vegetation Science 27:524-534.

Fraser, EC, VJ Lieffers and SM Landhausser. 2004. Wounding of aspen roots promotes suckering. Canadian Journal of Botany 82:310-315.

Frey, BR, VJ Lieffers, SM Landhäusser, PG Comeau and KJ Greenway. 2003a. An analysis of sucker regeneration of trembling aspen. Canadian Journal of Forest Research 33:1170-1176.

Frey, BR, VJ Lieffers, AD Munson and PV Blenis. 2003b. The influence of partial harvesting and forest floor disturbance on nutrient availability and understory vegetation in boreal mixedwoods. Canadian Journal of Forest Research 33:1180-1188.

Galipeau, C, D Kneeshaw and Y Bergeron. 1997. White spruce and balsam fir colonization of a site in the southeastern boreal forest as observed 68 years after fire. Canadian Journal of Forest Research 27:139-147.

Gärtner, SM, VJ Lieffers and SE Macdonald. 2011. Ecology and management of white spruce in the boreal forest. National Research Council. Environmental Review 19:461-478.

Ghose, MK. 2001. Management of topsoil for geoenvironmental reclamation of coal mining areas. Environmental Geology 40:1405-1410.

Gitte G and W Fast. 2007. Alberta making strides in mixedwood management. Forestry Chronicle 83:714-718.

Global Forest Watch Canada (2005). 2005 natural regions and Subregions of Alberta [map]. Scale not given. In: Maps – the last great intact forest landscapes of Canada: Atlas of Alberta: Part 1. On line at http://global forestwatch.ca/publications/20090402A_MapsI. Accessed 15 December 2016.

Gold, K and F Hay. 2014. Identifying desiccation-sensitive seeds. Millennium Seed Bank Partnership, Technical Information Sheet 10. Royal Botanic Gardens, Kew Victoria Australia. On line at http://www.kew.org/sites/default/files/10-Desiccation%20tolerance% 20web_0.pdf. Accessed 29 October 2016.

Government of Alberta. 2007. Forest and prairie protection act: the forest and prairie protection regulations. Part II. Alberta regulation 310/1972. Alberta Queen's Printer. Edmonton Alberta. 12 p.

Government of Alberta. 2011. Reclamation of specified land; 2010 reclamation criteria (Updated June 2011). On line at http://environment.alberta.ca/documents/2010-Reclamation-Criteria-Fact-Sheet.pdf. Accessed 20 September 2014.

Government of Alberta. 2013. Alberta oil sands industry quarterly update, summer 2013. On line at https://albertacanada.com/files/albertacanada/AOSIDQuarterly_Update_Summer2013.pdf. Accessed October 3, 2014.

Government of Alberta. 2014. Alberta Regulation 115/1993, environmental protection and enhancement act, conservation and reclamation regulation. Office Consolidation. Alberta Queen's Printer. Edmonton Alberta.

Government of Alberta. 2016. Vegetation inventory standards. Alberta Agriculture and Forestry. On line at http://www.agric.gov.ab.ca/app21/forestrypage?cat Forest%20Management. Accessed 2 August 2016.

Gradowski, T, D Sidders, T Keddy, VJ Lieffers and SM Landhäusser. 2008. Effects of overstory retention and site preparation on growth of planted white spruce seedlings in deciduous and coniferous dominated boreal plains mixedwoods. Forest Ecology and Management 255:3744-3749.

Grime, JP. 1979. Plant strategies and vegetation processes. John Wiley and Sons. Chichester New York. Pp 183.

Greene, DF, JC Zasada, L Sirois, D Kneeshaw, H Morin, I Charron and MJ Simard. 1999. A review of regeneration dynamics of North American boreal forest tree species. Canadian Journal of Forest Research 29:824-839.

Grover G, and W Fast. 2007. Alberta making strides in mixedwood management. Forestry Chronicle 83: 714-718.

Harmon, ME, JF Franklin, FJ Swanson, P Sollins, SV Gregory, JD Lattin, NH Anderson, SP Cline, NG Aumen, J Sedell, GW Lienkaemper, K Cromack Jr. and KW Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133-302.

Harris, HT. 1990. Populus balsamifera subsp. balsamifera. In: Fire effects information system, United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available at http://www.fs.fed.us/database/feis/tree/popbalb/all.html. Accessed 3 December 2016.

Hart, SA and HYH Chen. 2006. Understory vegetation dynamics of North American boreal forests. Critical Reviews in Plant Sciences 25:381-397.

Hassan, R, R Scholes and N Ash (eds). 2005. Ecosystems and human wellbeing: current state and trends. Vol. 1. Millennium ecosystem assessment series. Island Press. London, United Kingdom. 948 pp.

Hogg, EH, JP Brandt and B Kochtubajda. 2002. Growth and dieback of aspen forests in northwestern Alberta, Canada, in relation to climate and insects. Canadian Journal of Forest Research 32:823-832.

Howat, DR, 2000. Acceptable salinity, sodicity and pH values for boreal forest reclamation. Alberta Environment, Environmental Sciences Division, Edmonton Alberta. Report # ESD/LM/00-2. or ISBN 0-7785-1174-X. 191 pp.

Jean, PO, RL Bradley and JP Tremblay. 2015. Testing for bottom-up effects in an overbrowsed boreal landscape. Wildlife Biology 21:318-322.

Johnson, D, L Kershaw, A MacKinnon and J Pojar. 2009. Plants of the western boreal forest and aspen parkland. Lone Pine Publishing and the Canadian Forest Service. Edmonton Alberta. 392 pp.

Johnson, EA and K Miyanishi. 2007. Disturbance and succession. In: Plant disturbance ecology: the process and the response. Academic Press. Burlington Massachusetts. Pp 1-14.

Kabzems, R. 2012. Aspen and white spruce productivity is reduced by organic matter removal and soil compaction. Forestry Chronicle 88:306-316.

Kabzems, R, S Dube, M Curran, B Chapman, S Berch, G Hope, M Kranabetter and C Bulmer. 2010. Maintaining soil productivity in forest biomass chipping operations best management practices for soil conservation. British Columbia Ministry of Forests and Range, Forest Science Program. Victoria British Columbia. Extension Note 98. On line at www.for.gov.bc.ca/hfd/pubs /Docs/En/En98.htm. Accessed November 2016.

Kabzems, R and S Haeussler. 2005. Soil properties, aspen, and white spruce responses 5 years after organic matter removal and compaction treatments. Canadian Journal of Forest Research 35: 2045-2055.

Kenkel, NC, DJ Walker, PR Watson, RT Caners and RA Lastra. 1997. Vegetation dynamics in boreal forest ecosystems. Coenoses 12:97-108.

Kneeshaw, D, Y Bergeron and T Kuuluvainen. 2011. Forest ecosystem structure and disturbance dynamics across the circumboreal forest. In: A Millington, M Blumler and U Schickhoff (eds). The SAGE handbook of biogeography. SAGE Publications. London United Kingdom. Pp 261-278.

Kuuluvainen, T. 2002. Natural variability of forests as a reference for restoring and managing biological diversity in boreal Fennoscandia. Silva Fennica 36:97-125.

Koroleff, A, 1954. Leaf litter as a killer. Journal of Forestry 52:178-182.

Kreutzweiser, D, F Beall, K Webster, D Thompson and I Creed. 2013. Impacts and prognosis of natural resource development on aquatic biodiversity in Canada's boreal zone. Environmental Review 21:227-259.

Kroetsch, D and C Wang. 2008. Particle size distribution. Pages 713-725 In: MR Carter and EG Gregorich (eds). Soil sampling and methods of analysis. Canadian Society of Soil Science. CRC Press. Boca Raton Florida.

Kuuluvainen, T. 2002. Natural variability of forests as a reference for restoring and managing biological diversity in boreal Fennoscandia. Silva Fennica 36:97-125.

Landhäusser, SM and VJ Lieffers. 2001. Photosynthesis and carbon allocation of six boreal tree species grown in understory and open conditions. Tree Physiology 21:241-248.

Landhäusser, SM and VJ Lieffers. 1998. Growth of Populus tremuloides in association with Calamagrostis canadensis. Canadian Journal of Forest Research 28:396-401.

Landhäusser, SM, VJ Lieffers and P Chow. 2007. Impact of chipping residues and its leachate on the initiation and growth of aspen root suckers. Canadian Journal of Soil Science 87:361-367.

Landhäusser, SM, VJ Lieffers and U Silins. 2003. Utilizing pioneer species as a hydrological nurse crop to lower water table for reforestation of poorly drained boreal sites. Annals of Forest Science 60:741-748.

Landhäusser, SM, J Wachowski and VJ Lieffers. 2015. Transfer of live aspen root fragments, an effective tool for large-scale boreal forest reclamation. Canadian Journal of Forest Research 45:1056-1064.

LaRoi, GH and MHL Stringer. 1976. Ecological studies in the boreal spruce-fir forests of the North American taiga, II. Analysis of the bryophyte flora. Canadian Journal of Botany 54:619-643.

Laverty, DH and A Bollo-Kamara. 1988. Recommended methods of soil analyses for Canadian prairie agricultural soils. Report 300. Alberta Agriculture. Edmonton Alberta.

Legendre, P and L Legendre. 1998. Numerical ecology. Second edition. Elsevier Science. Amsterdam Netherlands. 853 pp plus appendices.

Lieffers, VJ, SE Macdonald and EH Hogg. 1993. Ecology of and control strategies for *Calamagrostis canadensis* in boreal forest sites, Canadian Journal of Forest Research 23:2070-2077.

Lieffers, VJ, KJ Stadt and S Navratil. 1996. Age structure and growth of understory white spruce under aspen. Canadian Journal of forest Research 26:1002-1007.

Lin, N, N Bartsch and T Vor. 2014. Long-term effects of gap creation and liming on understory vegetation with a focus on tree regeneration in a European beech (Fagus sylvatica L) forest. Annals of Forest Research 57:233-246.

Loeppert, RH and DL Suarez. 1996. Gravimetric method for loss of carbon dioxide. Pages 455-456 In: JM Bartels et al (eds). Methods of soil analysis: part 3 chemical methods. American Society of Agronomy and Soil Science Society of America. Madison Wisconsin.

Lupi, C, H Morin, A Deslauriers, S Rossi and D Houle. 2013. The role of soil nitrogen for the conifers of the boreal forest: a critical review. International Journal of Plant and Soil Science 2:155-189.

MacDonald, GB. 1995. The case for boreal mixedwood management: an Ontario perspective. The Forestry Chronicle 71:725-734.

Mackenzie, DD. 2013. Oil sands mine reclamation using boreal forest surface soil (LFH) in northern Alberta. PhD dissertation. Department of Renewable Resources, University of Alberta. Edmonton Alberta. 240 pp.

Mallik, AU and D Hu. 1997. Soil respiration following site preparation treatments in boreal mixedwood forest. Forest Ecology and Management 97:265-275.

Michaelian, M, EH Hogg RJ Hall and E Arsenault. 2011. Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. Global Change Biology 17: 2084–2094.

Miller, EM and TR Seastedt. 2009. Impacts of woodchip amendments and soil nutrient availability on understory vegetation establishment following thinning of a ponderosa pine forest. Forest Ecology and Management 258:263-272.

Miller, JJ and D Curtin. 2008. Electrical conductivity and soluble ions. Pages 161-172 In MR Carter and EG Gregorich (eds). Soil sampling and methods of analysis. Canadian Society of Soil Science and CRC Press. Boca Raton Florida.

Miller MR and SW May. 1979. Below-ground ecosystems project. Pages 64-70 In: Land Reclamation Program, Annual Report. 1978. Argonne National Laboratory, United States Department of Agriculture.

Molles Jr., MC. 2002. Ecology: concepts and applications. McGraw-Hill. New York, New York. Pp. 37-38.

Morris, DM and GB MacDonald. 1991. Development of a competition index for young conifer plantations established on boreal mixedwood sites. Forestry Chronicle 67:403-410.

Moss, EH. 1983. Flora of Alberta. Second edition. University of Toronto Press. Toronto Ontario. 687 pp.

Munson, AD, HA Margolis and DG Brand. 1993. Intensive silvicultural treatment: impacts on soil fertility and planted conifer response. Soil Science Society of America Journal 57:246-255.

Naeth, MA, R Brown and S Wilkinson. 2012. Use of woody debris as an amendment for reclamation after oil sands mining. Prepared for Canadian Oil Sands Network for Research and Development (CONRAD). Edmonton Alberta. 34pp.

National Research Council (US) Water Science and Technology Board (NRCWSTB). 2008. Forest disturbance and management effects on Hydrology. Pages 45-73. In: Hydrologic effects of a changing forest landscape. National Academies Press. Washington District of Columbia.

Natural Regions Committee 2006. Natural regions and subregions of Alberta. Compiled by DJ Downing and WW Pettapiece. Government of Alberta. Pub. No. T/852. Edmonton Alberta.

Navratil, S and DA MacIsaac. 1996. Juvenile growth of white spruce and deciduous competition on mixedwood sites in Alberta. Canadian Forest Service, Northern Forestry Centre. Edmonton Alberta. 116 pp.

Nelson, DW and LE Sommers. 1996. Total carbon, organic carbon and organic matter. Pages 961-1010 In: JM Bartels et al (eds). Methods of soil analysis: part 3 chemical methods. American Society of Agronomy and Soil Science Society of America. Madison Wisconsin.

Nguyen-Xuan, T, Y Bergeron, D Simard, JW Fyles and D Pare. 2000. The importance of forest floor disturbance in the early regeneration patterns of the boreal forest of western and central Quebec: a wildfire versus logging comparison. Canadian Journal of Forest Research 30:1353-1364.

Nienstaedt, H and JC Zasada. 1990. *Picea glauca* (Moench) Voss - White spruce, In: Silvics of North America: 1. Conifers, Agriculture Handbook No. 654, United States Department of Agriculture and Forest Service. Washington District of Columbia. Pp. 204-225.

Nishi, JS, S Berryman, JB Stelfox, A Garibaldi and J Straker. 2013. Fort McKay cumulative effects project: technical report of scenario modeling analyses with ALCES®. ALCES Landscape and Land Use. Calgary Alberta. Integral Ecology Group. Victoria British Columbia. Prepared for the Fort McKay Sustainability Department. Fort McMurray Alberta. 126 pp + 5.

Oil Sands Vegetation Reclamation Committee. 1998. Guidelines for reclamation to forest vegetation in the Athabasca oil sands region. First edition. ISBN 0-7785-0411-5. Alberta Environment Protection. Edmonton Alberta.

Oksanen, J, FG Blanchet, R Kindt, P Legendre, PR Minchin, RB O'Hara, GL Simpson, P Solymos, MHH Stevens and H Wagner. 2015. Package ‘vegan’; the community ecology package. On line at http://cran.r-project.org, https://github.com/vegandevs/vegan. Accessed 25 March 2015.

Osko, T and M Glasgow. 2010. Removing the wellsite footprint: recommended practices for construction and reclamation of wellsites on upland forests in boreal Alberta. Department of Biological Sciences, University of Alberta. Edmonton Alberta.

Paradis, E, J Claude and K Strimmer. 2004. Package ‘ape’: analyses of phylogenetics and evolution in R language. Bioinformatics 20:289-290.

Pastor, J and RJ Naiman. 1992. Selective foraging and ecosystem processes in boreal forests. The American Naturalist 39:690-705.

Peters, VS, SE Macdonald and RT Dale. 2006. Patterns of initial versus delayed regeneration of white spruce in boreal mixedwood succession. Canadian Journal of Forest Research 36:1597-1609.

Petroleum Geoscience Society. 2012. The Athabasca oil sands formation in the Lyell Collection of the Geological Society of London. On line at http://pgc.lyellcollection.org/content/ 7/1141 /F1.expansion.html. Accessed 12 October 2015.

Pinno, BD, SM Landhäusser, MD MacKenzie, SA Quideau and PS Chow. 2012. Trembling aspen seedling establishment, growth and response to fertilization on contrasting soils used in oil sands reclamation. Canadian Journal of Soil Science 92:143-151.

Pitt, DG, PG Comeau, WC Parker, D MacIsaac, S McPherson, MK Hoepting, A Stinson and M Mihajlovich. 2010. Early vegetation control for the regeneration of a single-cohort, intimate mixture of white spruce and trembling aspen on upland boreal sites. Canadian Journal of Forest Research 40:594-564.

Poos, MS and DA Jackson. 2011. Addressing the removal of rare species in multivariate bioassessments: the impact of methodological choices. Ecological Indicators 18:82-90.

Potvin, F, P Beaupre and G. Laprise. 2003. The eradication of balsam fir stands by white-tailed deer on Anticosti Island, Québec : a 150-year process. Ecoscience 10:487-495.

Powter, C, N Chymko, G Dinwoodie, D Howat, A Janz, R Puhlmann, T Richens, D Watson, H Sinton, K Ball, A Etmanski, B Patterson, L Brocke and R Dyer. 2012. Regulatory history of Alberta's industrial land conservation and reclamation program. Canadian Journal of Soil Science 92:39-51.

Purdy, BG, SE Macdonald and MRT Dale. 2002. The regeneration niche of white spruce following fire in the mixedwood boreal forest. Silva Fennica 36:289-306.

Pykälä, J. 2004. Immediate increase in plant species richness after clear-cutting of boreal herb-rich forests. Applied Vegetation Science 7:29-34.

Qi, MQ and JB Scarratt. 1998. Effect of harvesting method on seed bank dynamics in a boreal mixedwood forest in northwestern Ontario. Canadian Journal of Botany 76:872-883.

Quinn, G and M Keough. 2011. Experimental design and data analysis for biologists. Cambridge University Press. Cambridge United Kingdom. 537 pp.

R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna Austria. URL https://www.R-project.org/.

Renkema, KN, VJ Lieffers and SM Ländhausser. 2009. Aspen regeneration on log decking areas as influenced by season and duration of log storage. New Forests 38:323-335.

Rhodes AC, T Barney and SB St Clair. 2016. Stand composition, tree proximity and size have minimal effects on leaf function of coexisting aspen and subalpine fir. PLoS One 11: article number e0154395.

Ripley, B, B Venables, DM Bates, K Hornik, A Gebhardt and D Firth. 2016. Package 'MASS'; support functions and datasets for venables and Ripley's MASS. On line at https://cran.rproject. org/web/packages/MASS/MASS.pdf. Accessed 8 August 2016.

Roberts, DW. 2016. Package 'labdsv'; Ordination and multivariate analysis for ecology. On line at http://ecology.msu.montana.edu/labdsv/R. Accessed 4 August 2016.

Rosell, F, O Bozsér, P Collen and H Parker. 2005. Ecological impact of beaver *Castor fiber* and *Castor canadensis* and their ability to modify ecosystems. Mammal Review 35:248-276.

Rowe, JS. 1972. Forest regions of Canada. Fisheries and Environment Canada, Canadian Forest Service. Publication No.1300. Ottawa Ontario.

Schmidt, MG, SE Macdonald and RL Rothwell. 1996. Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta. Canadian Journal of Soil Science 76:531-540.

Schneider, R and S Dyer. 2006. Death by a thousand cuts; impacts of in situ oil sands development on Alberta's boreal forest. The Pembina Institute and Canadian Parks and Wilderness Society. Edmonton Alberta. ISBN 0-921719-83-3, 1st ed. 1:0-06-07-18.

Shepperd, WD. 1993. The effects of harvesting activities on soil compaction root damage and suckering in Colorado aspen. Western Journal of Applied Forestry 8:62-66.

Soil Classification Working Group. 1998. The Canadian system of soil classification. Agriculture and Agri-Food Canada. Publication number 1646 (Revised). 187 pp.

Startsev, AD and DH McNabb. 2007. Effects of compaction on aeration and morphology of boreal forest soils in Alberta, Canada. Canadian Journal of Soil Science 89:45-56.

Stone, DM and JD Elioff. 1998. Soil properties and aspen development five years after compaction and forest floor removal. Canadian Journal of Soil Science 78:51-58.

Straker, J and G Donald. 2011. Assessing re-establishment of functional forest ecosystems on reclaimed oil sands mine lands. On line at https://circle.Ubc.ca/bitstream/handle/2429/42303/Straker_J_et_al_BC2_Mine.pdf?sequence=1. Accessed 20 September 2014.

Suffling, R, C Lihou and Y Morand. 1988. Control of landscape diversity by catastrophic disturbance: a theory and a case study of fire in a Canadian boreal forest. Environmental Management 12:73-78.

Sutton, RF. 1969. Silvics of white spruce (*Picea glauca* (Moench) Voss). Canadian Forestry Service. Publication 1250. Ottawa, ON. 57 pp.

Tannas, K. 2001. Common plants of the western rangelands. Volume 1, Grasses and grass-like species. Olds College and Alberta Agriculture, Food and Rural Development. Lethbridge Alberta. 335 pp.

Tirmenstein, D. 1990. *Rubus idaeus*. In: Fire Effects Information System. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). On line at http://www.fs.fed.us/database/feis/. Accessed 17 August 2016.

Uchytil, RJ. 1991. Betula papyrifera. In: Fire effects information system, United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available at http://www.fs.fed.us/database/feis/. Accessed 3 December 2016.

United States Department of Agriculture (USDA). 2003. Quaking aspen *Populus tremuloides* Michx. In: Plant guide. United States Department of Agriculture and Natural Resources Conservation Service. On line at https://plants.usda.gov/plantguide/pdf/cs_potr5.pdf. Accessed 5 June 2016.

Venier, LA, ID Thompson, R Fleming, J Malcolm, I Aubin, JA Trofymow, D Langor, R Sturrock, C Patry, RO Outerbridge, SB Holmes, S Haeussler, L De Grandpré, HYH Chen, E Bayne, A Arsenault and JP Brandt. 2014. Effects of natural resource development on the terrestrial biodiversity of Canadian boreal forests. Environmental Review 22:457-490.

Vinge, T and M Pyper. 2012. Managing woody materials on industrial sites. Alberta School of Forest Science and Management, University of Alberta. Edmonton Alberta.

Visser, S, J Fujikawa, CL Griffiths and D Parkinson. 1984. Effect of topsoil storage on microbial activity primary production and decomposition potential. Plant and Soil 82:41-50.

Visser, S, D Maynard and RM Danielson. 1998. Response of ecto- and arbuscular mycorrhizal fungi to clear-cutting and the application of chipped aspen wood in a mixedwood site in Alberta, Canada. Applied Soil Ecology 7:257-269.

Vitousek, PM and JM Melillo.1979. Nitrate losses from disturbed forests: patterns and mechanisms. Forest Science 15:605-619.

Vitousek, PM, SW Andariese, PA Matson, L Morris and RL Sanford. 1992. Effects of harvest intensity, site preparation, and herbicide use on soil nitrogen transformations in a young loblolly pine plantation. Forest Ecology and Management 49: 277-292.

Vitousek, PM, JR Gosz, CC Grier, JM Melillo, WA Reiners and RL Todd. 1979. Nitrate losses from disturbed ecosystems. Science 204:469-474.

Waldron, RM 1966. Factors affecting natural white spruce regeneration on prepared seedbeds at the Riding Mountain Forest Experimental Area, Manitoba. Government of Canada, Department of Forestry and Rural Development, Forest Research Laboratory. Winnipeg Manitoba. Departmental publication 1169. 48 pp.

Wang, GG and K Klinka. 1996. Classification of moisture and aeration regimes in sub-boreal forest soils. Environmental Monitoring and Assessment 39:451-469.

Weber, E. 2011. Strong regeneration ability from rhizome fragments in two invasive clonal plants (Solidago canadensis and S. gigantea). Biological Invasions 13:2947-2955.

Weber, MG and BJ Stocks. 1998. Forest fires and Sustainability in the Boreal Forests of Canada. Ambio 27:545-550.

Wikipedia. 2014. History of the petroleum industry in Canada (oil sands and heavy oil). On line at http://en.wikipedia.org/wiki/History_of_the_petroleum_industry_in_Canada_ (oil_sands_ and_heavy_oil). Accessed September 10, 2014.

Zackrisson, O. 1977. Influence of forest fires on north Swedish boreal forest. Oikos 29:22-32.

Zasada, JC and RA Gregory. 1969. Regeneration of white spruce with reference to interior Alaska: a literature review. United States Department of Agriculture and Forest Service Research Paper PNW-79. Pacific Northwest forest and Range Experiment Station, Institute of Northern Forestry, and United States Department of Agriculture. Juneau Alaska. 37 pp.

APPENDIX A. PLANT SPECIES FOUND WITHIN FORESTED CONTROL SAMPLES ASSOCIATED WITH OIL SANDS EXPLORATION SITES

Table A.1. Plant species and relative abundance of each species (percent cover) found within forested control samples associated with OSE study sites in northern Alberta boreal forest, outlined in Table 2.1.

Species	Relative abundance	Species – Forbs continued	Relative abundance	Species – Forbs continued	Relative abundance
Species Grasses					
Agropyron repens	0.077	*Goodyera repens*	0.008	*Viola nephrophylla*	0.005
Agrostis stolonifera	0.003	*Gymnocarpium dryopteris*	0.056	*Viola renifolia*	0.145
Agropyron trachycaulum	0.009	*Habernia orbtusata*	0.002	Species Shrubs	
Bromus ciliatus	0.004	*Habernia orbiculata*	0.010	*Alnus crispa*	3.747
Calamagrostis canadensis	0.629	*Hieracium umbellatum*	0.017	*Alnus rugose*	0.103
Calamagrostis inexpansa	0.020	*Hypopitys monotropa*	0.002	*Amelanchier alnifolia*	0.186
Carex sp.	0.090	*Impatiens noli-tangere*	0.015	*Arctostaphylos uva-ursi*	0.903
Danthonia intermedia	0.009	*Lathyrus ochroleucus*	0.596	*Betula pumila*	0.009
Elymus innovatus	0.266	*Lathyrus venosus*	0.009	*Cornus stolonifera*	0.543
Poa palustris	0.003	*Lilium philadelphicum*	0.002	*Ledum groenlandicum*	1.554
Poa pratensis	0.021	*Linnea borealis*	4.483	*Lonicera dioica*	0.503
Achillea millefolium	0.038	*Lycopodium annotinum*	1.221	*Lonicera involucrate*	0.014
Species Forbs		*Lycopodium complanatum*	0.139	*Lonicera villosa*	0.053
Actea rubra	0.064	*Lycopodium obscurum*	0.128	*Prunus pensylvanica*	0.043
Aquilegia brevifolia	0.003	*Maianthemum canadense*	0.241	*Prunus virginianum*	0.034
Aralia nudicaulis	9.072	*Matteuccia struthiopteris*	0.072	*Ribes glandulosum*	0.078
Arenaria latifolia	0.016	*Melampyrum lineare*	0.001	*Ribes lacustre*	0.079
Aster ciliolatus	0.637	*Melilotus officinale*	0.001	*Ribes oxycanthoides*	0.243
Aster conspicuus	0.258	*Mertensia paniculata*	0.721	*Ribes triste*	1.857
Aster puniceus	0.012	*Mitella nuda*	2.000	*Rosa acicularis*	8.427
Cirsium alpine	0.076	*Monotropa uniflora*	0.001	*Rubus idaeus*	0.706
Cornus canadensis	7.139	*Orchid* sp.	0.022	*Salix* sp.	0.492
Disporum trachycarpum	0.120	*Osmorhiza depauperata*	0.047	*Shepherdia canadensis*	0.394
Dryopteris austriaca	0.086	*Pedicularis labradorica*	0.092	*Symphoricarpos albus*	0.191
Epilobium angustifolium	1.403	*Petasites palmatus*	1.516	*Vaccinium caespitosum*	0.026
Epilobium glandulosum	0.012	*Potentilla norvegica*	0.001	*Vaccinium myrtilloides*	0.765
Equisetum arvense	0.221	*Pyrola asarifolia*	0.437	*Vaccinium uliginosum*	0.009
Equisetum pratense	0.033	*Pyrola secunda*	0.136	*Vaccinium vitis-idaea*	0.003
Equisetum scirpoides	0.016	*Rubus pubescens*	2.647	*Viburnum edule*	7.228
Equisetum sylvaticum	0.200	*Spiranthes romanzoffiana*	0.003	Species Trees	
Erigeron philadelphicus	0.002	*Stellaria longifolia*	0.010	*Abies balsamea*	3.786
Fragaria vesca	0.033	*Taraxacum officinale*	0.020	*Betula papyrifera*	2.339
Fragaria virginiana	0.715	*Thalictrum venulosum*	0.003	*Larix laricina*	0.319
Galium boreal	0.278	*Trientalis borealis*	1.375	*Picea glauca*	9.285
Galeopsis tetrahit	0.003	*Urtica dioica*	0.017	*Picea mariana*	3.414
Galium triflorum	0.180	*Vicia americana*	0.074	*Pinus banksiana*	0.888
Galium trifidum	0.003	*Viola adunca*	0.347	*Populus balsamifera*	3.536
Geocaulon lividum	0.064	*Viola canadensis*	0.056	*Populus tremuloides*	30.016

APPENDIX B. COMPARATIVE REGENERATION DENSITY AND TOTAL DENSITY (STEMS M^{-2}) OF ALL TREE SPECIES BETWEEN SOIL TREATMENT GROUPS ON NORTHERN ALBERTA BOREAL WELL SITES.

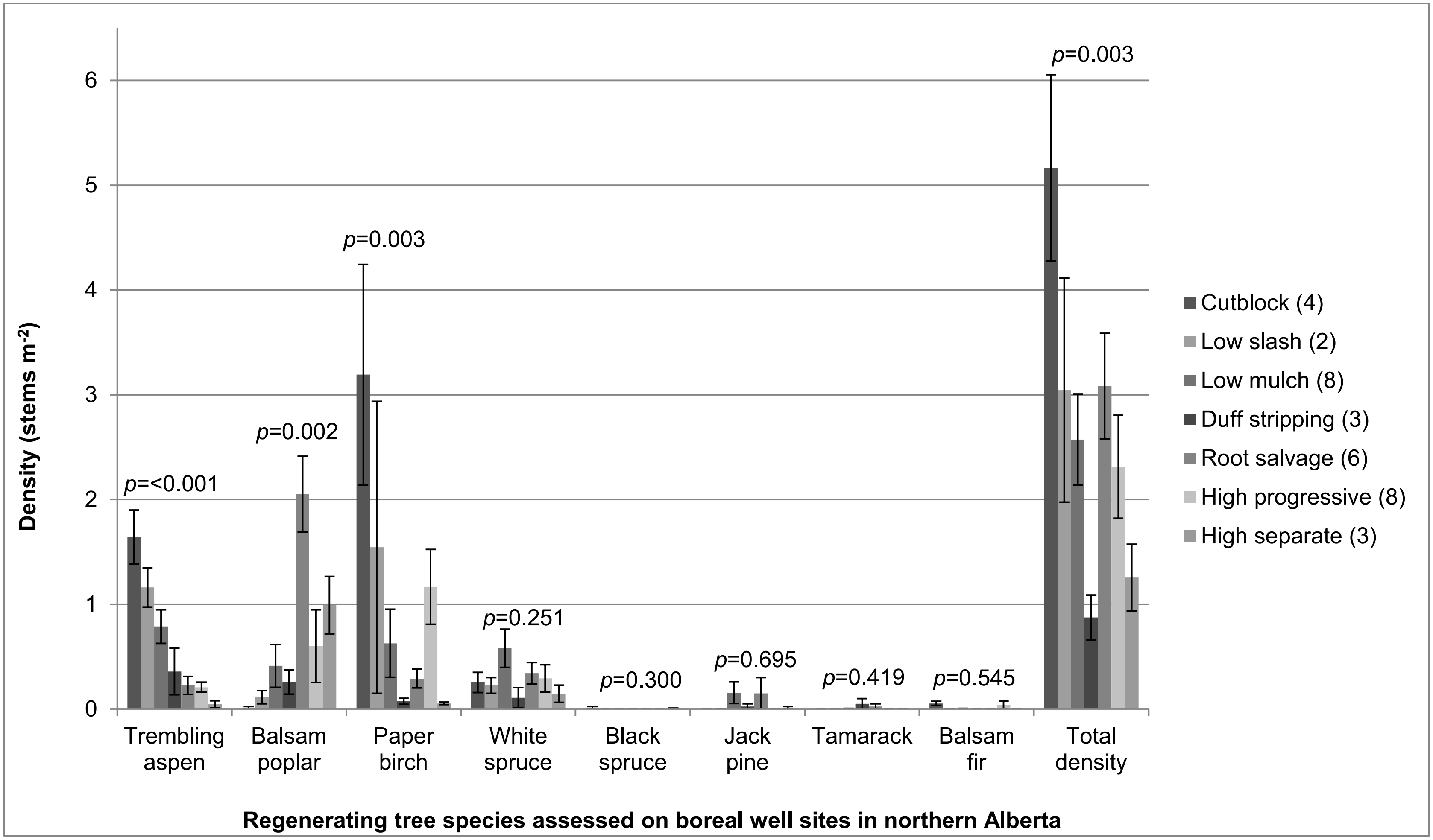

Figure B.1. Comparative regeneration density and total density (stems m^{-2}) of all tree species between soil treatment groups on northern Alberta boreal well sites. Above bars, p-values indicate significance of variation between groups based upon ANOVA. Numbers next to treatment group labels in legend indicate sample size (n). Mean comparisons of significant results using LSD tests are shown in Figure 3.3.