OIL SANDS RECLAMATION USING WOODY DEBRIS WITH LFH MINERAL SOIL MIX AND PEAT MINERAL SOIL MIX COVER SOILS: IMPACTS ON SELECT SOIL AND VEGETATION PROPERTIES

by

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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

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ABSTRACT

Prior to mining oil sands, soil is salvaged for reclamation and forest stands are harvested for their merchantable timber. Harvest operations leave large amounts of residual woody debris, which has been historically burned or mulched. Woody debris has significant ecological effects and can be used as an amendment to facilitate reclamation in the oil sands.

Influences of woody debris and soil cover types on select soil and vegetation properties were examined in years four and five after reclamation on a Suncor Energy Inc. overburden dump. Treatments consisted of no woody debris, black spruce woody debris or trembling aspen woody debris on LFH mineral soil mix or peat mineral soil mix soil covers. Soil properties assessed were near surface temperature, volumetric water content, plant available nutrients, total inorganic and organic carbon, total nitrogen, carbon to nitrogen ratio, sodium adsorption ratio, electrical conductivity, pH, texture and bulk density. Vegetation properties assessed were canopy cover, ground cover, vascular and non vascular species composition, richness, diversity and woody plant density. Woody debris volume and cover was assessed to determine application rates to provide optimal effects on vegetation establishment and soil properties.

Soil chemical and physical properties and volumetric water content were significantly affected by soil cover type. Woody debris and its size class contributed to regulating soil temperature. Woody debris continued to play a role in greater canopy cover for select vegetation properties; however, soil cover type had a more pronounced effect on various vegetation cover parameters, plant species richness, plant species composition and woody plant density. Woody debris volume application rates of 32.0 to 117.9 m^3/ha did not have negative effects on plant community development. Results show a continual positive relationship between woody debris and cover with soil and vegetation development in year five post reclamation, demonstrating the promotion of ecological succession on this disturbed landscape.

ACKNOWLEDGEMENTS

Thank you to the companies that funded this research: Canadian Natural Resources Ltd., Imperial Oil Resources Ltd., Shell Canada Energy, Suncor Energy Inc. and Syncrude Canada Ltd. Thank you to Canada's Oil Sands Innovation Alliance (COSIA), the Canadian Oil Sands Network for Research and Development, Environmental and Reclamation Group (CONRAD ERRG) and the Helmholtz Alberta Initiative (HAI) for their funding of this work. Thank you to the Natural Sciences and Engineering Research Council of Canada (NSERC) for awarding me an Alexander Graham Bell Canada Graduate Scholarship.

Thank you to the Suncor Closure Planning and Reclamation office, particularly Heather Archibald, Kristine Dahl, Christine Daly, Josh Martin and Francis Salifu for help with site access, safety training and field logistics.

Thank you to Robyn Brown for her contributions to the initial research plot establishment and for use of the data from 2008 and 2009.

Thank you to the many people from the Naeth research team at the University of Alberta for all your hard work in the field, the lab and/or in team meeting discussions: Jenna Abou Rizk, Jaime Aguilar Rojas, Heather Archibald, Varina Crisfield, Luke Fadum, Sarah Ficko, Kurt Forsch, Laurie Frerichs, Zhichao Jiao, Jasmine Lamarre, Edith Li, Gabriela Luna-Walter, Valerie Miller, Meghan Nannt, Robert Neys, Megan Rennie, Holly Stover, Lenore Turner and Marteya Yao.

Thank you to Heather Archibald, René Belland, Jasmine Lamarre, David Locky, Darin Sherritt and Holly Stover for help with plant identification.

A big thank you to Stacy Campbell Court, Michal Guzowski, Leanne McKinnon and Sarah Wilkinson for all your hard work coordinating annual reports, planning field seasons and logistics, organizing assistants and doing the countless other tasks you do to support the Naeth research team.

I am indebted to Heather Archibald, David Locky, Ellen Macdonald and Sarah Wilkinson for the statistical advice you provided in response to the many questions I had for my analyses.

A special shout out to Heather Archibald for her continued help and support in so many aspects of this project. You helped me with course work, field work, statistics and writing and were there for anything else I could possibly think of, including some very productive vent sessions. I may not have made it to the end without your support. I am forever grateful that this experience has developed a lifelong friendship between us.

Thank you to all my former and current colleagues at Matrix Solutions Inc. and Solstice Canada Corp. Thank you for your time, flexibility, understanding and advice when I needed it the most. The opportunity to grow my career, while continuing my education has been the biggest challenge I have ever faced. I am forever grateful for the mentorship and teamwork that has gotten me to where I am.

Thank you to my supervisory committee members, Dr. René Belland and Dr. David Chanasyk for your continued support, advice and expertise throughout this project. Thank you to my external examiner, Dr. Scott Chang.

Thank you to my supervisor Dr. M. Anne Naeth for being a mentor and an inspiration throughout this project. Thank you for your 'tough love' and never giving up on me, despite the frustrations that we faced. Your advice and support, not to mention superhuman powers in everything you do are what made this project a success. You were that constant push to have me succeed and words cannot express what that really means to me.

The biggest thanks go to the most important people in my life, my family. Thank you to my parents Floyd and Greta Forsch, my siblings Kirsten Fargey, Kiera Brunka and Kurt Forsch, my in-laws Joe and Debbie Frison, Jodi Maher and Jesse Frison and all the significant others including Scott Fargey, Graham Brunka, Whitney Diakur and Brendan Maher. You can finally stop asking me how my thesis is going. I know many of you still don't understand what I've been studying for the last three years, but now you'll be able to download a document with three year's worth of work etched into 118 pages. I thank you for your understanding and encouragement and believing in me every step of the way. I couldn't ask for a better support system in my life.

I also can't forget to thank my dog Turbo, who sat on my lap almost every day I spent on my laptop for this project. I know you'll never read this, but your presence was an immense comfort to me, especially when I needed it the most.

Above all, thank you to my husband, Justin Frison. I think you are more excited about my finishing this thesis than I am. I know it took a lot longer than we both would have liked, but your encouragement to the very end goes beyond words. Thank you for being by my side throughout this long journey. Thank you for believing in me. Thank you for your patience. Thank you for your love.

Enough crying now, let's get on to the thesis.

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CHAPTER I. INTRODUCTION

1. BACKGROUND

Woody debris is defined as any type of dead woody material including logs, branches, twigs, cones, dead roots, buried wood, snags and stumps (Harmon et al. 1986, Hély et al. 2000, Brown 2010, Brown and Naeth 2014). Woody debris is a critical component of forest ecosystems, contributing to plant community structure, productivity, microhabitat diversity, water retention, erosion control, nutrient and mineral cycling, energy fluxes and soil formation (Harmon et al. 1986, Rambo and Muir 1998, Hély et al. 2000, Ódor and Standovár 2001, Rambo 2001, Shorohova and Shorohov 2001, Ódor et al. 2006, Brown 2010, Brown and Naeth 2014). Woody debris influences microclimate conditions such as light, soil temperature, air humidity and nutrients, and protects against wind, light and drought (Andersson and Hytteborn 1991, Mills and Macdonald 2004, Botting and Fredeen 2006). These conditions, along with wood decay longevity, species growth, dispersal and colonization, increase microhabitat variety for vascular and non vascular plants (Crites and Dale 1998) and can substantially influence plant diversity. Woody debris functions as habitat and food for various other organisms including fungi, invertebrates, birds and mammals, thus playing an important role in maintaining biodiversity in forest ecosystems.

Understanding ecological successional processes and the relationships among woody debris, soils and plants is very important in the reclamation and management of disturbed landscapes for sustainable biodiversity. Reclamation strategies can mimic natural ecological succession by providing microclimate conditions naturally associated with woody debris. Examining trends in vegetation, soils and woody debris decay characteristics, will help to determine factors that facilitate development of sustainable plant communities (Botting and Fredeen 2006, Botting and DeLong 2009) after reclamation.

Thus this MSc research program focused on evaluating whether woody debris on LFH mineral soil mix and peat mineral soil mix soil covers contributes to successful land reclamation. This project investigated woody debris impacts on plant community succession and soil substrates of large scale reclamation areas in the Athabasca Oil Sands Region of Alberta. The study was conducted on a research site in years four and five after reclamation, following an MSc research program that studied the site in year one (after construction) and year two (Brown 2010, Brown and Naeth 2014), to determine longer term impacts of the woody debris and soil cover material.

2. LITERATURE REVIEW

2.1 Boreal Forest Ecosystem

The Boreal Forest Natural Region is characterized by a continental, relatively humid climate with short, warm summers and long, cold winters (Natural Resources Canada 2007). Mean annual temperature for the Fort McMurray area is 0.7 °C with a mean daily maximum of 23.2 °C in July and a mean daily minimum of -24 °C in January (Environment Canada 2010). Mean annual precipitation is 455.5 mm, with 342.2 mm as rain and 155.8 cm as snow. On average there are 97 frost free days (Natural Regions Committee 2006).

Topography of the Central Mixed Wood Natural Subregion consists of gently undulating plains with minor inclusions of hummocky uplands (Natural Regions Committee 2006). Underlying bedrock is of Cretaceous shales with minor inclusions of sandstones and siltstones in the south and Devonian limestones, shales and siltstones in the northeast. Bedrock is of McMurray and Clearwater formations. Parent materials include coarse to fine textured tills, fine textured glaciolacustrine deposits, coarse textured fluvial and eolian deposits and organic deposits. Gray Luvisols dominate in uplands, with Dystric and Eutric Brunisols associated with coarse textured soils. Peatlands and wetlands are dominated by organic Mesisols and minor Fibrisols, Cryosols and Orthic and peaty Gleysols.

Upland forests are dominated by *Picea glauca* (Moench) Voss (white spruce), *Populus tremuloides* Michx. (trembling aspen) and mixed stands on fine textured soils (Natural Regions Committee 2006, Natural Resources Canada 2007). *Abies balsamea* (L.) Mill. (balsam fir), *Betula papyrifera* Marsh. (paper birch), *Populus balsamifera* L. (balsam poplar) and *Pinus banksiana* Lamb. (jack pine) occur, with *Pinus banksiana* forests dominating coarse soils. Peatlands and wetlands dominated by *Larix laricina* (Du Roi) K. Koch (tamarack) and *Picea mariana* (P. Mill.) B.S.P. (black spruce) fens and bogs cover almost half the area.

2.2 Oil Sands Mining Disturbance

The Athabasca oil sands in Alberta have a reserve of 1.6 to 1.7 trillion barrels of bitumen; the largest single oil deposit in the world (Johnson and Miyanishi 2008, Marlowe 2011). Approximately 142,000 km^2 of Alberta is covered by oil sand deposits in Athabasca, Cold Lake and Peace River regions (Alberta Department of Energy 2006, Government of Alberta 2013) with 4,800 km^2 extractable by open pit mining (Alberta Department of Energy 2006).

Approximately 767 km^2 has been disturbed by oil sands mining (Government of Alberta 2013), with reclamation first beginning at Suncor Energy Inc. in 1971 (Brown 2010).

Mining extracts bitumen and upgrades it to marketable synthetic crude oil (Alberta Department of Energy 2006). Prior to oil sands extraction from open pits surface vegetation, muskeg, topsoil and overburden consisting of rock, clay and non bituminous sands are removed. Topsoil is salvaged separate from subsoil and stockpiled for application during reclamation. Direct placement of salvaged soil material is beneficial to maintaining viable seed sources for reclamation, but is limited during construction and operations for various reasons. Fine tailings are produced from bitumen refinement, consisting of fine grained material mixed with residual tailings, and left to settle in large holding ponds (National Energy Board 2000).

2.3 Oil Sands Reclamation

Mining companies are legally obligated by the Alberta Provincial Government to reclaim land to pre disturbance conditions that have equivalent land capability and the natural range of variability found in the boreal forest region (Oil Sands Revegetation Reclamation Committee 1998, Government of Alberta 2013). Equivalent land capability is defined as "the ability of the reclaimed land to support land uses similar to what existed prior to an activity, but the land uses will not necessarily be the same" (Alberta Environment 2010a). Only 104 ha of land disturbed by oil sands mining is certified reclaimed, with 5,042 ha permanently reclaimed to date (Government of Alberta 2013). Alberta Environment and Sustainable Resource Development, Alberta Energy Regulator and Alberta Energy Resources Conservation Board are governing bodies that regulate oil sands operations. Environmental Protection and Enhancement Act approvals are required to construct and operate facilities in Alberta and include conservation and reclamation plans that stipulate the reclamation process for each project at closure (Government of Alberta 2000a). Reclamation in the Athabasca oil sands targets land capable of supporting self-sustaining, locally common boreal forest ecosystems, regardless of end land use (Alberta Environment 2007). Commercial forests and non-commercial forests are main end land use categories in the Athabasca Oil Sands Region. End land uses for non-commercial forests include wildlife habitat, recreation or traditional use (Alberta Environment 2010a).

Current reclamation practices include applying salvaged topsoil to disturbed landscapes using peat mineral soil mix or LFH mineral soil mix, also known as upland surface soil or forest floor mineral mix (Naeth et al. 2013). LFH mineral soil mix includes shallow salvaged LFH layers and underlying mineral horizons (A horizon) of upland soil. Topsoil material is an excellent source of seeds and plant propagules (MacKenzie and Naeth 2007, Mackenzie and Naeth 2010); it can increase soil microorganisms and nutrient availability and improve soil water holding capacity (Winter Syndor and Redente 2002). Although peat mineral soil mix was historically used as topsoil, LFH mineral soil mix is now a primary material for reclamation. It contains more upland plant seeds and propagules and functions as a better cover than peat mineral soil mix (Mackenzie 2006, MacKenzie and Naeth 2007, Mackenzie and Naeth 2010, Mackenzie 2012).

Revegetation historically focused on erosion control. Plant community development relied on planting desired species and encroachment of others from surrounding areas (Alberta Environment 2010a). Revegetation techniques included seeding annual nurse crops of *Hordeum vulgare* L. (common barley), which dies year after year (Oil Sands Revegetation Reclamation Committee 1998). The increasing *Hordeum vulgare* litter and root biomass provide erosion control and help to facilitate favourable site conditions for trees, shrubs and forbs to establish from soil cover seed sources. Current revegetation in the Athabasca Oil Sands Region is based on ecosite/site type or end land use approaches (Alberta Environment 2010a). The ecosite/site type approach is based on selecting revegetation treatments by site conditions as determined by the Land Capability Classification System soil water and nutrient regimes and target ecosite/site type. The end land use approach is determined by target end land use and treatment methods to achieve stand objectives.

2.4 Soil Cover Type In Oil Sands Reclamation

Two main soil substrate types traditionally prescribed for oil sands reclamation are peat mineral soil mix and LFH mineral soil mix. Peat mineral soil mix is widely available and has been used for over 25 years (Fenske 2012). Peat mineral soil mix makes up volumes required for cover soil when upland materials, including LFH mineral soil mix have limited availability (Alberta Environment and Water 2012).

Organic soils that comprise a component of peat mineral soil mix are characterized by low wind and water erosion potential and high available water holding capacity, which is favourable to improve water use efficiency early in reclamation (Alberta Environment and Water 2012, Fenske 2012). Other properties of organic soils include low or high pH and low buffering capacity, limitations to soil temperature and nutrients, high carbon to nitrogen (C:N) ratio and lack of plant propagules and seed bank material conducive to upland reclamation sites (Mackenzie 2006). Specific soil properties vary depending on the organic soil source and whether it is fen or bog peat (Alberta Environment and Water 2012). Limiting macronutrients in peat mineral soil mix reclamation materials require fertilizer to offset the C:N ratio. Peat is mixed with various mineral soil mixes to improve tilth and to reduce loss of organic matter from rapid decomposition.

LFH mineral soil mix is the preferred oil sands reclamation cover soil for reclamation of upland areas, although it has the most limited availability in the Athabasca Oil Sands Region. LFH mineral soil mix provides vascular and non vascular plant vegetative propagules and seeds for reclamation and has suitable physical and chemical properties to be a superior plant growth medium to peat mineral soil mix (McMillan 2005, Mackenzie 2006, Mackenzie and Naeth 2010, Brown 2010, Hahn 2012, Mackenzie and Quideau 2012, Mackenzie 2012, Brown and Naeth 2014). It is rich in organic matter, macro and micronutrients and has a C:N ratio and pH comparable to that of undisturbed upland forests (Alberta Environment and Water 2012). Microbial community composition of LFH mineral soil mix, including soil macro invertebrates and meso and micro fauna is similar to that of natural forests (Hahn 2012). Most approvals currently require its salvage and use in reclamation (Alberta Environment 2007).

2.5 Woody Debris In Oil Sands Reclamation

Historical management of woody debris on industrial sites in forested areas included piling and burning and mulching. Piling and burning was based on the Forest and Prairies Protection Act, which dictates complete disposal of woody materials following industrial clearing to mitigate fire hazards created by stockpiling (Government of Alberta 2000b). The primary mandate of fire control limits preservation of woody material for ecosystem recovery. Mulching is often used by exploration companies and has added value when applied properly to alleviate soil erosion and minimize environmental footprints. A recent perception shift was attributed to evidence that piling and burning increased human caused wildfires (CAPP 2008). Fine mulching is considered inhibitive to reclamation because at depths greater than 4 cm, it has negative effects, such as insulating soil to create frozen layers longer into the growing season that inhibit plant emergence (Corns and Maynard 1998, MacIsaac et al. 2003, Landhäusser et al. 2007, Government of Alberta 2009). Fine mulch immobilizes nutrients, resulting in high C:N ratios. Leachates can be toxic in aquatic systems (Taylor and Carmichael 2003) and mulching is not allowed within 30 m of a riparian area (Government of Alberta 2009).

Current management strategies for woody debris in the Athabasca Oil Sands Region include piling and burning, mulching, rough mulching, breaking logs into chunks and stockpiling non merchantable whole logs that will be spread once active site operations are completed (Vinge and Pyper 2013). Recent regulations, including the Reclamation Criteria for Wellsites and

Associated Facilities, recognize the ecological value of woody debris and encourage its use to facilitate reclamation (ESRD 2013). The Management of Wood Chips on Public Lands directive recognizes wood chipping to provide erosion control and protect soil resources (Government of Alberta 2009). This directive supports use of coarse woody debris to promote microtopography as a source of water storage, erosion control and facilitate plant and animal diversity.

Few studies have determined effects of using woody debris as an amendment in land reclamation. Most evidence for beneficial use comes from studies on old growth forests and forest stands impacted by management and harvesting practices (Harmon et al. 1986). Other studies identified the usefulness of woody debris for erosion control (Stevens 1997, Whisenant 2005, Debeljak 2006).

Dimitriu et al. (2010) studied surface mining in the Athabasca Oil Sands Region and found 10.1 % of the variance between phospholipid fatty acid profiles in natural and reclaimed soils was explained by woody debris. Brown (2010) and Brown and Naeth (2014) found that in early succession, plant survival and health were promoted by woody debris and there were positive relationships between woody debris and species richness, vegetation cover and woody plant density. Woody debris treatments had fewer introduced species and vegetation had greater evenness. *Picea mariana* woody debris functioned as a propagule source for *Picea mariana* seedlings. During initial stages of plant community development, plants grew in close proximity to woody debris; however, as microsites were created by other plants, plants spread away from woody debris microsites. Greater soil water content occurred in association with woody debris and larger soil temperature ranges were associated with no woody debris. Brown (2010) and Brown and Naeth (2014) found there was lower available nitrate, higher available phosphorus and lower microbial biomass carbon with woody debris. Lower nitrate likely resulted from immobilization in woody debris (Harmon et al. 1986, Laiho and Prescott 1999) and higher available phosphorus was likely from woody debris leachate (Auerswald and Weigand 1996, Krankina et al. 1999, Kuehne et al. 2008).

Recommended application rates of woody debris volume and cover on reclamation sites are limited to company specific best management practices and literature reviews of natural inputs to forest ecosystems in the boreal forest. The volume of woody material in forested areas has a natural range of variability and varies with forest stand (Vinge and Pyper 2013). Woody debris volumes of 25 to 250 m^3/ha have been found in boreal forest (Harmon et al. 1986, Densmore et al. 2004), but studies specific to Alberta suggest volumes of 45 to 100 m^3/ha are within the local natural range of variability (Lee et al. 1997). Vinge and Pyper (2013) recommend application rates of 60 to 100 m3/ha or 10 to 25 % coverage on upland reclaimed sites and 30 to 50 m3/ha on lowland sites to reflect the natural range of variability in lowland areas. This rate is based on historical natural forest inputs, stand volumes of harvested sites and similar reviews by the United States Department of Agriculture (Brown et al. 2003). This range balances mitigating fire concerns while promoting ecological value of woody materials.

Intact woody debris pieces of various sizes are important to generate the highest ecological value for reclamation from woody debris application (Harmon et al. 1986, Vinge and Pyper 2013). Variability of lengths and sizes reflects stages of decomposition that play important roles throughout succession of a regenerating plant community. Size of woody debris pieces affects total coverage on a reclamation site. Intact, whole logs are preferred as they provide erosion control, water retention, microsites and heterogeneity in the landscape (Vinge and Pyper 2013).

2.6 Ecological Effects Of Woody Debris

Woody debris is important to nutrient cycling in forest ecosystems and may be essential for nutrient retention and productivity following a major disturbance (Rambo 2001, Laiho and Prescott 2004). Woody debris comprises a greater volume and 20 to 30 % of total woody biomass in a natural forest than in many disturbed areas (Shorohova and Shorohov 2001, Stokland 2001). In newly forested areas, woody biomass from woody debris increased to almost 70 % with removal of live vegetation. Woody debris functions as a large reservoir of organic carbon, accounting for over 50 % of forest floor and soil organic matter (Shorohova and Shorohov 2001, Laiho and Prescott 2004). Woody debris contributes to a high C:N ratio and carbon cycling during early development of forest ecosystems (Laiho and Prescott 2004). It provides low (less than 20 %) nitrogen, phosphorus, potassium, calcium, magnesium and exchangeable cations (Qian et al. 1999, Laiho and Prescott 2004) due to low concentrations in woody debris and a slower rate of decomposition than other litter types (Laiho and Prescott 2004). Woody debris initially acts as a sink for growth limiting nutrients such as nitrogen and phosphorus, but as it decays concentrations increase. This is largely driven by carbon loss and nutrient mobilization. It can take several decades before woody debris starts to act as a nitrogen source. Nitrogen in decaying wood may increase because of fixation in logs. Woody debris from early forests may be a substantial nutrient pool for disturbed areas.

Woody debris microsites provide a unique and highly suitable substrate for plant growth by providing humidity and nutrients (Qian et al. 1999, Fenton et al. 2007). Woody debris contributes to geomorphologic processes and physical and chemical properties of decaying woody debris are important to soil development (Qian et al.1999, Shorohova and Shorohov 2001). Kushnevskaya et al. (2007) found that structure and composition of plant communities highly dependent on woody debris were associated with decaying wood characteristics such as species, decay stage, bark cover, pH, density and texture. As woody debris decays, it becomes softer and spongier, allowing it to retain more water resulting in high water holding capacity (Rambo and Muir 1998, Qian et al. 1999). This enables woody debris to buffer the surrounding microclimate during drought or reduced precipitation (Rambo and Muir 1998). Bark types of woody debris have varying thickness and shading. A thick bark with more shading increases water retention (Turner and Pharo 2005). Decayed woody debris has microhabitats not present in fresh, undecayed woody debris, such as deep crevices, which provide shade and control water flow. As woody debris decomposes, increased air humidity and activity of decomposers enrich the ambient air with carbon dioxide (Rambo and Muir 1998, Laiho and Prescott 2004). The ability of woody debris to retain water is important for soil organic matter accumulation by creating desirable conditions for microorganisms and other decomposers, resulting in accelerated primary productivity and enhanced element cycling.

Decaying woody debris is an important structural component of undisturbed forests (Rambo 2001). Decay progresses from recently fallen trees to logs, which become nearly indistinguishable from forest floor humus with time (Rambo and Muir 1998). Decay stage has a significant effect on plant community biodiversity and is important in determining species composition of wood inhabiting plants (Caruso and Rudolphi 2009). Species richness increases as decay class increases.

Woody debris provides microhabitat diversity significantly affecting bryophyte diversity and function in boreal forest ecosystems and created open microsites for rapid colonization by early successional species (Ohlson et al. 1997, Økland et al. 2008). Bryophyte distributions, community composition, diversity and richness are strongly influenced by heterogeneity, distribution and availability of microhabitats (Cole et al. 2008, Økland et al. 2008). Bryophyte community composition varied with hydrologic conditions and was affected by tree species and diameter (Jansová and Soldán 2006).

Decayed woody debris supports microhabitat specific species (Cole et al. 2008). A large amount of woody debris in various decay stages provides more diverse microhabitats and microclimate conditions for bryophytes, resulting in greater species richness and abundance (Crites and Dale 1998, Rambo 2001, Ódor and Hees 2004, Cole et al. 2008). Composition of bryophytes on woody debris is correlated with physical and chemical properties resulting from woody debris decay (Jansová and Soldán 2006). Rambo (2001) found woody debris in advanced decay stages had the richest bryophyte flora and Botting and Fredeen (2006) found mosses were more diverse and evenly distributed in old growth forests. Crites and Dale (1998) found old mixed wood forests had highest bryophyte species richness and greatest diversity of woody substrates for each subsequent decay stage. Caruso and Rudolphi (2009) found younger age class forests (4 to 9 years) had significantly lower species richness than older age class forests (12 to 18 years). Botting and DeLong (2009) found feather moss cover increased from almost none on woody debris in early decay stages to up to 81 % in later decay stages. Species cover on woody debris in early decay stages increased from less than 5 % to almost 100 % in advanced decay stages. Differences in properties, such as water holding capacity of young bark versus old bark, may explain preferential bryophyte species (Turner and Pharo 2005).

Size of woody debris plays a key role in bryophyte species richness. Large logs are preferred by bryophytes, but in disturbed areas, amount and quality of dead wood is limited and woody debris is usually small and in early decay stages, decreasing bryophyte species richness (Ódor and Standovár 2001, Stokland 2001, Jansová and Soldán 2006). Large decaying logs provide a larger area and longer time for colonization due to a slower rate of decay than fine woody debris that produces thin, rapidly decaying material (Ódor and Standovár 2001, Ódor and Hees 2004, Ódor et al. 2006). More microhabitats occur on large woody debris and large diameter logs are less likely to be overgrown and covered by soil, ground flora and litter than small, rapidly decaying fine woody debris (Ódor and Hees 2004, Jansová and Soldán 2006, Ódor et al. 2006, Kushnevskaya et al. 2007). Bryophyte flora on fine woody debris is poor and dominated by common species, whereas on large woody debris it is rich, with more rare species occasionally occurring (Ódor and Hees 2004).

2.7 Woody Debris Characterization And Classification

Many classes for woody debris have been developed over time to quantify woody debris decay stages; the most common class currently used is by Yan et al. (2006). These decay classes are based on a number of attributes. Decay classes are ranked from class 1, being least decayed, to class 5, being most decayed and are associated with stages of succession (Botting and DeLong 2009). Decay class 1 is characterized by presence of bark, leaves and branches and solid wood consistency, with the wood cambium still fresh (Brown 2010). The opposite extreme, decay class 5, is characterized by absence of leaves, branches and bark and a soft, powdery wood consistency that a knife can easily penetrate.

Woody debris species, substrate quality and woody debris diameter and microclimatic factors such as temperature, soil contact and soil water have a strong influence on rate of woody debris decay (Shorohova and Shorohov 2001, Stokland 2001, Laiho and Prescott 2004). Decomposition rate can be expressed as a decay rate constant (k) calculated as: $Y_t = Y_0 e^{-kt}$ where Y_0 is the initial quantity of the material and Y_t is the quantity remaining at time t (Laiho and Prescott 2004). Stokland (2001) found woody debris with less than 10 cm diameter decomposed faster as diameter decreased, but woody debris with diameters greater than 10 cm decomposed at slightly slower rates.

Stokland (2001) and Jansová and Soldán (2006) found woody debris on exposed east or north facing slopes, which receive less sunlight and retain greater soil water longer than other aspects, had higher decay rates. Woody debris from deciduous species such as *Populus tremuloides* and *Betula papyrifera* generally decayed more rapidly than woody debris from conifers (Stokland 2001). Substrate characteristics affecting decay rate included carbohydrate composition; phosphorus, potassium and calcium concentrations; air temperature; substrate water content, texture, softness, pH and water holding capacity (Laiho and Prescott 2004, Jansová and Soldán 2006). Decay accelerated with increased water content up to a point; too much water impeded decay by limiting aeration (Laiho and Prescott 2004). The relationship between log diameter (surface area to volume ratio) and decay rate varies with substrate quality and water content. Northerly areas have slow decay rates. During decay, wood density decreases and water holding capacity increases along with increases in nitrogen, phosphorus and sulphur concentrations (Ódor and Hees 2004).

2.8 Ecological Succession

Succession refers to the process of change in an ecological community following disturbance over time (Connell and Slatyer 1977, Botting and DeLong 2009). Mechanisms that drive succession are physical stresses to plants, competition for resources and interactions with herbivores, predators and pathogens (Connell and Slatyer 1977). Succession can change plant community characteristics such as biomass, productivity, composition and diversity. Stage of woody debris decay, size and microclimate conditions can influence plant community succession significantly (Rambo and Muir 1998, Caruso and Rudolphi 2009).

Two main types of succession are primary and secondary. Primary succession occurs on newly formed soils lacking vegetation (Finegan 1984) such as areas with glacial moraines, recent eolian deposits and areas disturbed by volcanic eruptions (Walker and de Moral 2003).

Secondary succession occurs on disturbed areas with soils and remnants of a plant community such as areas disturbed by forest fires, logging or flooding. Colonizing plants are the focus of primary succession, whereas secondary succession can have colonizing plants, but plant community development depends chiefly on existing viable seeds and plant propagules (Walker and de Moral 2003, Mackenzie 2006).

Two examples of models of succession that are applicable to boreal forest ecosystems are Egler's (1954) initial floristic composition and Connell and Slatyer's (1977) tolerance model (Mackenzie 2006). The initial floristic composition model describes succession proceeding from propagules, the limiting factor for succession following disturbance (Kenkel et al. 1997). The tolerance model describes succession based on a group of species that is most efficient at exploiting limiting resources (Connell and Slatyer 1977, Mackenzie 2006). Initially, pioneer and colonizing species establish and are displaced by later successional species more tolerant to declining resources (Walker and de Moral 2003). Other models include facilitation and inhibition (Connell and Slayter 1977) and Grime's three basic plant life history strategies are ruderals, stress tolerators and competitors (Kenkel et al. 1997, Mackenzie 2006).

Connell and Slatyer (1977) describe a succession model where only early successional species colonize and adapt to conditions of a disturbed site because of their evolved characteristics including large numbers of propagules, dormancy persistence and ability to quickly and effectively, disperse, germinate and establish. These pioneer species improve disturbed conditions by reducing pH, increasing nitrogen, adding organic soil, reducing wind desiccation, stabilizing soils and creating a suitable environment for later succession species to invade. An alternative model suggests early colonists do not affect establishment of later successional species, which are always present, but require lower levels of resources and are more tolerant of environmental factors such as shade, water, nutrients and grazing than early successional species. Thus, later successional species dominate when more tolerant site conditions occur.

There are important biological characteristics to consider when determining species and plant assemblages that will appear at various stages of succession. Late successional species grow slower than early successional species (Connell and Slatyer 1977). Species that can reproduce vegetatively and sexually can dominate and persist for a long time. Stability in the plant community can only occur on a larger scale by accommodating several species. Change in species composition depends on stability. Regardless of the successional pathway, it is nearly impossible for a plant community to reach steady state equilibrium, making succession a continuous, evolving process.

Succession in boreal forest follows a multi-directional successional pathway (Finegan 1984, McCook 1994, Cook 1996, Mackenzie 2006). The boreal forest is a disturbance driven ecosystem (Rowe 1961). With forest fires so common in the boreal forest, each area disturbed by fire is unique and the pattern of succession to a climax plant community is difficult to predict (Cogbill 1985, McCook 1994; Kenkal et al. 1997). Wildfires, insect outbreaks and tree fall occur frequently in the boreal forest and often keep these areas in early successional stages (Rydgren et al. 1998, Mackenzie 2006).

The successional pathway of an area in the boreal forest disturbed by fire depends on fire frequency, with regeneration favouring quick growing, shade intolerant species and seed bank ephemerals (Kenkel et al. 1997, Mackenzie 2006). Short lived species of upland forest areas could be *Rubus idaeus* L., *Epilobium angustifolium* (L.) Holub., *Populus* spp., *Betula* spp. or any other species that rapidly establishes in direct sunlight. *Pinus* spp. is adapted to frequent fire intervals and will regenerate quickly in recently burned upland and lowland ecosystems. It can outlive pioneer species and exists in old growth stands. Death of some pioneer species creates openings in the canopy that triggers nutrient cycling and releases resources for mid to later successional species, such as *Picea* spp. and *Abies* spp., which are shade tolerant (Little 2001, Mackenzie 2006).

3. RESEARCH OBJECTIVES AND THESIS ORGANIZATION

The objective of this research was to evaluate ecological effects of using woody debris as an amendment to facilitate reclamation of disturbed landscapes in the Athabasca Oil Sands Region. A research site constructed in 2007 (year one) and 2008 was analyzed in years four and five after reclamation. The research site had six treatment combinations consisting of no woody debris or woody debris from *Picea mariana* or *Populus tremuloides* mixed wood forests on LFH mineral soil mix and peat mineral soil mix covered substrates.

In Chapter II research is presented on effects of woody debris on LFH mineral soil mix and peat mineral mix soil cover treatments in year four after reclamation to determine effects on select soil properties. Specific objectives were as follows.

- Determine the impacts of woody debris and soil cover types on chemical and physical soil properties (soil surface temperature, volumetric water content, plant available nutrients, total inorganic and organic carbon, total nitrogen, carbon to nitrogen ratio, sodium adsorption ratio, electrical conductivity, pH, texture, bulk density).

- Determine if the above impacts are affected by woody debris size.

In Chapter III research is presented on vegetation properties in years four and five after reclamation to determine relationships of woody debris and soil cover types on plant community succession. Specific objectives were as follows.

- Determine the impacts of woody debris and soil cover type on vegetation properties (canopy cover, ground cover, vascular and non vascular species composition, richness, diversity, woody plant density).
- Determine if the above impacts are affected by woody debris size.
- Determine optimal cover and volume application rates for woody debris.

In Chapter IV a summary is presented of key conclusions, research limitations, applications to reclamation practices and future research.

Chapters in this thesis are meant to stand alone. As a result, there may be some duplication of figures, tables and site description sections. All references cited are contained at the end of the thesis as per University of Alberta requirements.

CHAPTER II. WOODY DEBRIS AND SOIL COVER TYPE IMPACTS ON SELECT SOIL PROPERTIES AFTER OIL SANDS MINE RECLAMATION

1. INTRODUCTION

Woody debris is any type of dead woody material and is a critical component of forest ecosystems around the world. Woody debris contributes to plant community structure, productivity, microhabitat diversity, water retention, erosion control, nutrient and mineral cycling, energy fluxes and soil formation processes (Harmon et al. 1986, Rambo and Muir 1998, Hély et al. 2000, Ódor and Standovár 2001, Rambo 2001, Shorohova and Shorohov 2001, Ódor et al. 2006, Brown 2010, Brown and Naeth 2014). Woody debris inputs in the Boreal Forest Natural Region contribute to successional processes of multi-directional, dynamic forest ecosystems (Finegan 1984, McCook 1994, Cook 1996, Mackenzie 2006). The ecological value woody debris provides to these sustainable ecosystems is of particular interest for reclamation of disturbed boreal forests.

Approximately 767 km^2 of land in Alberta has been disturbed by oil sands mining (Government of Alberta 2013), with the majority of this disturbed area occurring in the Boreal Forest Natural Region. Reclamation of open pit mines began at Suncor Energy Inc. in 1971 (Brown 2010). Since then, 104 ha have been certified reclaimed, with an additional 5,042 ha permanently reclaimed, but not certified (Government of Alberta 2013). The goal of oil sands mine reclamation is to reclaim disturbed areas to equivalent land capability of what existed prior to an activity (Alberta Environment 2010a). This presents a challenge to develop sustainable reclaimed systems on a large scale, with available material.

Two main components of reclamation that influence development of sustainable ecosystems include topsoil placement and revegetation. Two materials used for topsoiling include peat mineral soil mix and LFH mineral soil mix, also known as upland surface soil or forest floor mineral mix (Naeth et al. 2013). Peat mineral soil mix was historically used because of its availability; however, LFH mineral soil mix provides a superior growth medium for plants relative to peat mineral soil mix (MacMillan et al. 2006, Mackenzie 2006, Mackenzie and Naeth 2010, Brown 2010, Hahn 2012, Mackenzie and Quideau 2012, Mackenzie 2012, Brown and Naeth 2014). LFH mineral soil mix is a rich source of organic matter, macro and micronutrients and has a carbon to nitrogen (C:N) ratio and pH comparable to undisturbed upland forests (Alberta Environment and Water 2012). Ecosystem recovery with LFH mineral soil mix cover promotes rapid revegetation with native, favourable species that comprises a sustainable reclaimed ecosystem in disturbed oil sands mining areas.

Other methods to expedite ecosystem recovery after oil sands mining usually involve materials available at the time of reclamation. Fertilizer and annual nurse crops have historically been used to stimulate plant growth and control wind and water erosion. Woody debris cleared from neighbouring disturbances is a readily available and economic resource that can facilitate ecosystem recovery and plant community development of large scale disturbances. Historical management of woody debris includes piling and burning and mulching (Government of Alberta 2009). More recent regulations recognize the ecological value of using woody debris and encourage its use in reclamation (ESRD 2013).

Use of woody debris in reclamation is a relatively new area of research, with few studies focused on effects of woody debris on ecosystem recovery. Many mining companies have developed standard woody debris handling practices; however, many of these approaches are based on trial and error applications and have been directed mainly to erosion control. One study directly addressed use of woody debris for reclamation (Brown 2010, Brown and Naeth 2014). However, this study was of short duration and only covered the first two years of effects. Longer term effects of woody debris and soil cover types are expected, particularly as the woody debris begins to decompose and vegetation on the site matures. No field based research has been conducted to directly examine woody debris volume application rates for reclamation applications. Current best management practices for recommended volume application rates are based on a review of the literature on natural inputs from woody debris to natural boreal forests (Vinge and Pyper 2013).

2. RESEARCH OBJECTIVES

The overall objective of this research was to evaluate ecological effects of using woody debris as an amendment to facilitate reclamation of disturbed landscapes in the Athabasca Oil Sands Region in years four and five after reclamation. Specific research objectives were as follows.

- Determine the impacts of woody debris and soil cover type on select soil chemical and physical properties (surface temperature, volumetric water content, plant available nutrients, total inorganic and organic carbon, total nitrogen, carbon to nitrogen (C:N) ratio, sodium adsorption ratio, electrical conductivity, pH, texture, bulk density).
- Determine if the above impacts are affected by woody debris size.

3. MATERIALS AND METHODS

3.1 Study Area

The research study area is located on the Suncor Energy Inc. (Suncor) oil sands mine, in the Athabasca Oil Sands Region of Alberta, approximately 30 km north of Fort McMurray, Alberta (Figure 2.1). The research site is in the Central Mixed Wood Natural Subregion of the Boreal Forest Natural Region (Natural Regions Committee 2006).

The Boreal Forest Natural Region is characterized by a continental climate with short, warm summers and long, cold winters (Natural Resources Canada 2007). Mean annual temperature for the Fort McMurray area is 0.7 °C, with a mean daily maximum of 23.2 °C in July and a mean daily minimum of -24 °C in January (Environment Canada 2010). Mean annual precipitation is 455.5 mm, with 342.2 mm falling as rain and 155.8 cm falling as snow. On average there are approximately 97 frost free days (Natural Regions Committee 2006).

Topography of the Central Mixed Wood Natural Subregion consists mainly of gently undulating plains with minor inclusions of hummocky uplands (Natural Regions Committee 2006). The underlying bedrock is composed of Cretaceous shales with minor inclusions of sandstones and siltstones in the south and minor inclusions of Devonian limestones, shales and siltstones in the northeast. Bedrock geology is generally of the McMurray and Clearwater formations. Parent materials include coarse to fine textured tills, fine textured glaciolacustrine deposits, coarse textured fluvial and eolian deposits and organic deposits. Gray Luvisols mainly dominate the upland soils, with Dystric and Eutric Brunisols associated with coarse textured soils. Peatland and wetland soils are mainly dominated by organic Mesisols and minor Fibrisols, Cryosols and Orthic and peaty Gleysols.

Vegetation of the Central Mixed Wood Natural Subregion mainly consists of upland forests and lowland peatlands. Upland forests are dominated by *Picea glauca* (Moench) Voss (white spruce), *Populus tremuloides* Michx. (trembling aspen) and other mixed stands on fine textured soils (Natural Regions Committee 2006, Natural Resources Canada 2007). *Abies balsamea* (L.) Mill. (balsam fir), *Betula papyrifera* Marsh. (paper birch), *Populus balsamifera* L. (balsam poplar) and *Pinus banksiana* Lamb. (jack pine) occur in upland forests, with *Pinus banksiana* forests dominating the coarse textured soils. Peatlands and wetlands cover almost half of the study area and are dominated by *Larix laricina* (Du Roi) K. Koch (tamarack) and *Picea mariana* (P. Mill.) B.S.P. (black spruce) fens and bogs.

3.2 Research Site Location And Construction

The research site is located on the southeast dump (SE dump) of Suncor Energy Inc., occupying an area of 70 by 300 m on a mid slope, with a southeast facing aspect (Brown 2010). The site was cleared in 1999 and used as a dump for saline sodic overburden waste until 2004. Research plot construction began in November 2007 and was completed in February 2008.

Plots were constructed on an operational scale and involved soil cover placement, followed by woody debris application from November 22 to December 2, 2007. Additional woody debris was salvaged and placed from February 12 to 14, 2008. All woody debris was salvaged from a nearby area, then directly placed without any stockpiling time. A 100 cm cap of clean overburden separated treatments from saline sodic overburden. LFH mineral soil mix was salvaged to 20 cm, stockpiled 3 months and applied at 20 cm over 30 cm of B and C horizon mixed subsoil. LFH mineral soil mix was salvaged from mesic (b and d) ecosites with *Populus tremuloides*, *Picea glauca* and *Pinus banksiana* (Archibald 2014); no material properties information from the LFH donor site was obtained. Peat mineral soil mix was applied at 30 cm on clean overburden; no material properties from the donor site or stockpile information on peat mineral soil mix were obtained. Soil materials were spread with a D6 Caterpillar bulldozer and woody debris was placed using a grapple hoe. Plots were aerially fertilized in June 2008 with 23.5:25:8 (nitrogen:phosphorus:potassium) fertilizer at 300 kg/ha and in August 2009 with a 31.5:16:5 fertilizer at 250 kg/ha with a fixed wing aircraft (Brown 2010). They were again aerially fertilized in June 2010 and 2011 using granular urea 46:0:0, monoammonium phosphate 11:52:0 and muriate of potash 0:0:60 fertilizers.

Meteorological conditions in the study area varied from plot construction to the end of the study in 2012 (Appendix B). In year one accumulated precipitation was similar to long term normals; years two (2009) and four (2011) were substantially drier. Year five (2012) was wetter than the long term normals by over 50 mm. Temperature differences between years varied seasonally relative to the long term normals. June, July and august air temperatures were higher than long term normals in all years after plot construction. 2010 had the highest yearly temperature mean, followed by 2011 and 2012. 2008 and 2009 were more than 1 °C cooler than other years.

3.3 Experimental Design

Six research treatment combinations consisted of no woody debris or woody debris from *Picea mariana* or *Populus tremuloides* mixed wood forests placed on LFH mineral soil mix and peat mineral soil mix covered substrates. Woody debris treatments, including controls with no woody debris are hereafter referred to as woody debris type; LFH mineral soil mix and peat mineral soil mix covered substrates are hereafter referred to as soil cover type. Two rows of plots were horizontally placed along a slope in a complete randomized block design. Each block was 10 m wide by 30 m long (Figure 2.2) and each row had three replicates of each treatment for a total of 36 treatment plots. A 5 m buffer separated plots and a 10 m buffer separated rows. Slopes in the bottom row (6 to 11 %) were steeper than in the top row (2 to 8 %). Half the plots had LFH mineral soil mix applied at a depth of 20 cm, over 30 cm of B and C mix horizon subsoil and 100 cm of clean overburden. The other half had peat mineral soil mix applied at a depth of 30 cm, over 100 cm of clean overburden.

For each soil cover type, six plots had *Picea mariana* woody debris, six had *Populus tremuloides* mixed wood woody debris and six were controls with no woody debris (Figure 2.2). *Populus tremuloides* mixed woody debris contained approximately 70 % *Populus tremuloides*, 30 % *Picea glauca* and traces of *Betula papyrifera* (Brown 2010). All debris was arranged in a vertical direction (down slope) in plots and placed to provide maximum contact with the soil surface. Mean woody debris cover for *Populus tremuloides* mixed wood treatments after construction was 11 %; *Picea mariana* treatment mean was 20 % due to greater abundance of small and fine sized woody debris. Woody debris size classes were fine woody debris with diameter less than 2 cm, small woody debris with diameter 2 to 5 cm, medium woody debris with diameter 5 to 15 cm and large woody debris with diameter greater than 15 cm.

3.4 Soil Sampling And Laboratory Analyses

Soil samples were collected in each plot for chemical analyses using a dutch auger in July 2011 after vegetation assessment. For plots with woody debris, two hand samples were collected in the top 20 cm of soil; one under a randomly selected large woody debris piece and one under a small woody debris piece. In controls, one sample was collected in the top 20 cm of soil from a random location in each plot. Samples were sealed in plastic bags and refrigerated (4 to 5 °C) until analyzed. Bulk density samples were collected at the soil surface adjacent to the chemical parameter soil sample using a double cylinder uhland core sampler (7.5 cm diameter, 13 cm length) (McKeague 1978). Up to five subsamples were taken in one plot representing each treatment combination to assess within plot variability.

Soils were analyzed at a commercial laboratory according to methods detailed in Carter and Gregorich (2008) unless noted. Available nitrogen was determined by extraction, available phosphorus and potassium by modified Kelowna extraction, available sulphate (SO_4) by inductively coupled plasma atomic emission spectrophotometry. Total nitrogen and total carbon were determined by dry combustion. Inorganic carbon was determined by CO_2 release. Total organic carbon was calculated by subtracting total inorganic carbon from total carbon. C:N ratio was the ratio of total carbon to total nitrogen.

Electrical conductivity, sodium adsorption ratio and pH were determined by saturated paste. Particle size analysis (sand, silt, clay) was determined by hydrometer. Bulk density samples were oven dried at 105 °C. Wet and dry weights were used to calculate bulk density, which was used to infer settling and compaction of the soil surface beneath small and large woody debris.

3.5 Soil Temperature And Soil Volumetric Water Content

HOBO micro station data loggers (Onset Computer Corporation, Bourne, MA) with plug-in smart sensors were used to assess soil volumetric water content and surface temperature. Three replications of treatment locations and instrumentation had been installed in August 2008 in the bottom row plots on relatively level ground. For each treatment, a single multiple parameter sensor that could record both soil volumetric water content and soil surface temperature was placed at 5 cm depth below the soil surface; one under a large and one under a small piece of woody debris in *Picea mariana* and *Populus tremuloides* woody debris plots. One sensor was randomly installed at 5 cm depth in control plots. Daily data were collected hourly from August 2008 to August 2012. A calibration equation (Appendix A) was based on newly collected and previous data sets from the site were used for volumetric water content for each soil cover type (Heidman 2011).

Dates that had missing soil temperature and soil volumetric water content data that resulted from equipment error were removed from the data set prior to calculation of treatment means based on a reduced sample number. Negative values in water content data were replaced with zeros to calculate treatment means.

3.6 Statistical Analyses

A mixed model analysis of variance (ANOVA) was used to compare soil chemical and physical parameters within treatment combinations with three factors of interest (block, soil cover, woody debris) using SAS statistical software (version 9.2, SAS Statistical Institute). Rows were treated as blocks and each plot as an experimental unit. Treatment types (soil cover, woody debris) were fixed factors in the mixed model analysis; block was treated as a random factor. Treatments with subsamples had a mean taken from corresponding subsamples to have a mean sample per plot.

The Shapiro-Wilk test was used to determine if residuals of treatment combinations followed a normal distribution and Levene's test was used to assess homogeneity of variance. For many soil parameters, outliers resulted in failure of normality and homogeneity of variance tests. Scatter plots were examined to assess outliers; these outliers were not outside the range of variability previously reported for these materials in these areas (Paragon and Jacques Whitford Axys 2009) and thus they were not removed from the data sets for analyses. Results with p-values of 0.03 or greater were considered to have passed the test for normality as ANOVA is fairly robust and can account for these minor abnormalities associated with small sample sizes ($n = 6$). For parameters with treatment combinations that failed the test for normality, but passed the homogeneity of variance test, parametric tests were used for the remaining analyses, to account for a small sample size that may attribute to non normal data. All parameters passed Levene's homogeneity of variance test.

A three way ANOVA using proc mixed in SAS accounted for differences in variances. Significant interactions were examined using interaction plots of the least square means and performing an analysis of simple effects using the slice statement in SAS. The slice statement performs a partitioned analysis of least square means for an interaction (SAS Institute Inc. 2009). Post hoc comparisons by Tukey's test were used to examine significant interactions.

Two sample t-tests were used to compare select soil chemical data from 2009 (Brown 2010) with 2011 data. Parameters were analyzed first with peat mineral soil mix and LFH mineral soil mix covers combined and then by soil cover separately to examine differences among years and covers. Parametric student's t-tests were used when data passed normality tests and non parametric Wilcoxon-Mann-Whitney t-tests when data failed normality tests. T-tests were considered significant at $p < 0.05$ for parametric tests and $p < 0.100$ for non parametric tests, which are conservative with much lower power than parametric tests (Dytham 2011). Statistical analyses were not completed for available nitrogen or available ammonium as most values were below detection limits.

Data from HOBO micro station data loggers from August 2008 to August 2012 were used to calculate weekly mean soil temperature ranges and soil volumetric water content for 52 weeks of the year. Data were analyzed using two-way ANOVAs as they were only recorded in one block. Treatment types (soil cover, woody debris, size class) were fixed factors, but were analyzed separately in group combinations (soil cover vs woody debris, size class vs woody debris for LFH mineral soil mix and peat mineral soil mix) to maintain a two-way ANOVA design. The non parametric Kruskal-Wallis test or Scheirer-Ray-Hare extension of the Kruskal Wallis test (Scheirer et al. 1976) was used because data failed tests for normality and homogeneity of variance. Proc glm was used in SAS after ranking data with proc rank to generate mean square values of model and factors. Mean square values were applied in the Scheirer-Ray-Hare test, which was run in R (version 2.12.1, R Development Team). ANOVAs were run in two groups with the first test including cover and woody debris as fixed factors with controls with no woody debris. The second test included woody debris and size class as fixed factors, with controls removed for a two-way ANOVA. This test was run on data from both soil covers then separately on LFH mineral soil mix and peat mineral mix. Significance was at $p < 0.100$ since non parametric tests are conservative with much lower power than parametric tests (Dytham 2011).

4. RESULTS AND DISCUSSION

4.1 Effect Of Woody Debris And Soil Cover Type On Soil Chemical Properties

In year four after reclamation, available nitrate and ammonium were often below analytical detection limits (Table 2.1). Both were numerically higher in LFH mineral soil mix than in peat mineral soil mix. LFH mineral soil mix had significantly more available phosphorus ($p < 0.0001$) and potassium ($p = 0.0072$) than peat mineral soil mix, which had significantly more available sulfate ($p = 0.0142$). Total nitrogen and organic carbon had significant block and soil cover type (total nitrogen $p = 0.0357$; total organic carbon $p = 0.0484$) interactions. Peat mineral soil mix had significantly more total inorganic carbon ($p = 0.0022$) than LFH mineral soil mix. C:N ratio was significantly higher ($p = 0.0149$) in LFH mineral soil mix than peat mineral soil mix, with a significant block and soil cover type ($p = 0.0170$) interaction.

Peat mineral soil mix pH was significantly higher ($p < 0.0001$) than LFH mineral soil mix, with block as a significant factor ($p = 0.0137$), resulting in a significant block and soil cover ($p = 0.0008$) interaction (Table 2.1). Higher pH in peat mineral soil mix reflects the source material from fen peat or moderate rich fen ecosites. The slightly acidic pH of LFH mineral soil mix suggests the material source was under a deciduous-coniferous mix forest stand.

Sodium adsorption ratio and electrical conductivity were significantly greater (sodium adsorption ratio $p = 0.0112$; electrical conductivity $p = 0.0032$) in peat mineral soil mix than in LFH mineral soil mix (Table 2.1), with block acting as a significant factor for sodium adsorption ratio. Mean values were below Alberta Tier 1 Salt Remediation Guidelines (Alberta Environment 2010b). The mean value for the peat mineral soil mix control treatment (Table 2.4) equaled the threshold for soil salinity deductions and suitability ratings under the Land Capability Classification System (CEMA 2006) and Soil Quality Criteria Relative to Disturbance and Reclamation (AAFRD 1987).

Total organic carbon, total nitrogen, available phosphorus and pH did not change significantly over time in either LFH mineral soil mix or peat mineral soil mix (Table 2.2). Available potassium, C:N ratio, electrical conductivity and sodium adsorption ratio increased under both soil covers from 2009 to 2011. Compounding results of small decreases in total nitrogen and small increases in total organic carbon over time may have resulted in the significant increase in C:N ratio. Available sulfate did not differ between years in peat mineral soil mix, but increased significantly with time in LFH mineral soil mix. These results suggest that changes in soil parameters over time may be related to changes in soil development processes, which are likely occurring slowly on the reclaimed site.

Phosphorus occurred in lower concentrations under large woody debris than small woody debris and was lowest in both peat mineral soil mix and LFH mineral soil mix controls (Tables 2.3, 2.4). Control treatments had higher available sulfate concentrations and higher sodium adsorption ratios than any treatments with woody debris.

There was no significant effect of woody debris type or woody debris presence or absence on soil chemical properties. Size of woody debris pieces was not analyzed statistically, but numerically had variable effects on soil properties with either soil cover type (Tables 2.3, 2.4). In LFH mineral soil mix, available sulfate was numerically higher under large *Populus tremuloides* woody debris pieces than under small woody debris pieces in LFH mineral soil mix treatments; available phosphorus, potassium and sulfate were numerically higher under small *Picea mariana* woody debris for both soil cover types.

In early stages of decomposition, woody debris is high in phosphorus, which leaches from the woody debris through the soil (Auerswald and Weigand 1996, Kuehne et al. 2008). Large woody debris pieces decompose slower than small woody debris pieces, so phosphorus would not leach as quickly. Lower available phosphorus in controls without woody debris than with woody debris may indicate woody debris contributes to increased phosphorus in the soil and early decomposition of woody debris is occurring.

Available nitrogen and ammonium were below detection limits four years following placement of woody debris. At the time of plot construction, woody debris was fresh and undergoing little to no decomposition. When woody debris begins to decompose, it immobilizes nitrogen in the soil and creates unfavourable C:N ratios that inhibit plant growth. Decomposition has not reached a stage where nitrogen in the soil is beginning to immobilize. Physical break down of bark and small woody debris is occurring, but chemical decomposition is slow.

4.2 Effect Of Woody Debris And Soil Cover Type On Soil Physical Properties

Woody debris type and size class and soil cover type had few significant effects on soil physical properties (Tables 2.1, 2.2, 2.3, 2.4). LFH mineral soil mix had significantly higher silt content ($p < 0.0001$) than peat mineral soil mix; peat mineral soil mix had significantly higher clay content ($p < 0.0001$) (Table 2.1). Bulk density and sand content had a significant block and soil cover type (bulk density $p = 0.0218$; sand content $p = 0.0195$) interaction. All treatments had loam or sandy loam textured soils.

Significant differences in soil texture and sand, clay and silt content are attributed to source parent material and proportions of mixed LFH and peat layers with mineral horizons salvaged below. Higher bulk density in LFH mineral soil mix may be caused by mixing salvaged A horizons from upland forest areas, which occur within the top 20 to 30 cm of the soil profile. A horizon bulk densities are 1.30 to 1.45 Mg/m^3, higher than the 0.10 Mg/m^3 of LFH horizons and 0.06 to 0.18 Mg/m^3 of Of, Om and Oh (peat) horizons (Brierley 2008). Therefore, when salvaging an LFH and A horizon mix of an upland forest soil, resultant bulk density is higher than salvaging only an O horizon of a peaty lowland.

4.3 Effect Of Woody Debris And Soil Cover Type On Soil Temperature

Weekly mean soil temperature range is the difference between the mean high and the mean low soil temperature within a week. Soil weekly mean temperature ranges had a statistically significant interaction ($p < 0.0001$) with woody debris and soil cover type. There was a significant interaction ($p = 0.0265$) between size class and woody debris when both soil covers were analyzed together. There was a significant interaction ($p < 0.0929$) with size class and woody debris type in peat mineral soil mix when soil covers were analyzed separately; however, only size class was significant ($p < 0.0001$) in LFH mineral soil mix.

Soil temperature followed a clear trend throughout the study, with greater mean ranges of daily, weekly (Figure 2.3) and monthly temperature under small woody debris greater than under large woody debris. Controls with no woody debris had similar fluctuations to small woody debris pieces. There was no trend between soil temperature and soil cover type. A temporal trend showed temperature ranges decreased since from August 2008 to August 2012.

Weekly extreme soil temperature range is the difference between the lowest and the highest soil temperatures within a given week (Figure 2.4). Weekly extreme soil temperature ranges showed a pronounced effect of differences in site conditions under small and large woody debris pieces. There were greater fluctuations between weekly lows and weekly highs under small woody debris than under large woody debris. The extreme high and low temperatures of controls were similar to those of small woody debris. Extreme ranges were quite high; 17.5 °C under peat mineral soil mix controls the week of June 11, 2009 to approximately 7.5 °C under peat mineral soil mix large *Populus tremuloides*, a 10.0 °C difference. Three years later, extreme ranges were lower at only approximately 11.0 °C the week of June 10, 2012 under peat mineral soil mix small *Picea mariana* and 3.0 °C under peat mineral soil mix large *Populus tremuloides*, a temperature difference of 8.0 °C.

In winter 2009, peat mineral soil mix had lower temperatures than LFH mineral soil mix (Figure 2.5). In winter 2010, LFH mineral soil mix had lower temperatures than peat mineral soil mix. Weekly mean soil temperatures between November 2008 and March 2009 were -5.5 to 1.0 °C in peat mineral soil mix and -1.5 to 1.0 °C in LFH mineral soil mix. The following year, weekly mean soil temperatures between November 2009 and March 2010 were -4.0 to 1.5 °C in peat mineral soil mix and -7 to 2.0 °C in LFH mineral soil mix. In winters 2011 and 2012, both covers had approximately the same weekly mean temperature. Throughout summer, peat mineral soil mix had higher temperatures than LFH mineral soil mix.

Throughout the study, ranges in daily, weekly and monthly temperatures were greater under small woody debris than under large woody debris. Smaller fluctuations in soil temperature are likely a result of relatively more uniform microsites created by shade and insulation of soil provided by large pieces. The cover of small woody debris pieces lacks the buffering capacity associated with large pieces to moderate site conditions and protect the soil surface from elements, such as rain and sun exposure. A greater cover of many small pieces would increase the ability of woody debris to protect against rain and sun (water evaporation from the soil surface, increased soil temperatures), but could cause other undesirable effects, such as reduced space for plant emergence.

Similar temperature fluctuations in controls with no woody debris and small woody debris pieces implies small woody debris contributes relatively little to moderating site conditions that aid in initial establishment of early successional plant species (Brown 2010, Brown and Naeth 2014).

Large pieces provide more beneficial effects for soil surface conditions including soil surface temperature. Large fluctuations in soil surface temperature create unfavourable site conditions that have a greater effect on native plants than aggressive, introduced species that are adapted to survive and thrive in harsh or unstable environments. This predisposes the site to invasion by undesirable species that could outcompete desirable, native species that are more sensitive to unstable, variable conditions.

Brown (2010) and Brown and Naeth (2014) found temperature ranges under large woody debris were approximately 3 °C less than controls. These results are consistent with 2012 data, in that soil temperature high and low ranges under large pieces were less than under controls in years four and five after reclamation. From 2009 to 2012, soil temperature range magnitudes under all treatments decreased and effects were less pronounced. Stabilization or reduction of variability in soil temperatures between 2008 and 2012 may be attributed to the plant community. As vegetation developed and grew around woody debris pieces, it may have played the role that woody debris played earlier in creating uniform microsites, regulating soil surface temperatures and decreasing evaporation that seed germination and seedling emergence depend on (Fowler 1988, Oswald and Neuenschwander 1993, Jones and del Moral 2005). Vegetation may be providing enough shade and protection to moderate microsites within the soil covers. Brown (2010) and Brown and Naeth (2014) showed that in the year following reclamation, vascular and non vascular plant growth was greatest close to woody debris, but after the first year only bryophytes and woody plants showed significant response to woody debris. These results can be attributed to hydrologic and temperature stability in soil covers surrounding woody debris. These findings continued in years four and five and benefits of microsite stability provided by woody debris may be further transferred to the plant community.

Brown (2010) and Brown and Naeth (2014) found that soil temperature ranges under large *Picea mariana* logs were 5 °C less than controls and temperature under large *Populus tremuloides* logs was about 7 °C less than controls. No difference between species of woody debris was found in years four and five following reclamation. This suggests that any trend following initial reclamation may have been situational and is not representative of the overall trend in woody debris type.

Large woody debris provides the greatest benefit to soil surface temperature regulation and is the preferred size class for reclamation applications. Large woody debris has greater cover than small woody debris and provides increased protection for seedlings from desiccation, wind and frost damage (Harmon et al. 1986, Vinge and Pyper 2013). Although overall effects of woody debris may decrease over time as its role begins to interact with the surrounding, developing vegetation, its use continues to stabilize soil surface temperatures and site conditions and is essential to early ecosystem regeneration and development. Oil sands disturbances are large scale with little protection from harsh environmental conditions. Resources, such as cleared woody debris, that mitigate harsh site conditions and expedite ecosystem regeneration should be used where and when they are available.

4.4 Effect Of Woody Debris And Soil Cover Type On Soil Volumetric Water Content

Weekly mean soil volumetric water content fluctuated seasonally and clearly was affected by soil cover type (Figure 2.6). Weekly mean soil volumetric water content had a statistically significant interaction ($p < 0.0001$) with woody debris and soil cover types. There was a significant interaction ($p < 0.0001$) between size class and woody debris type when both soil cover types were analyzed together. There was a significant interaction between size class and woody debris type when LFH mineral soil mix ($p = 0.0006$) and peat mineral soil mix ($p < 0.0001$) were analyzed separately.

Soil volumetric water content showed a clear trend throughout the study, having higher daily, weekly and monthly means in peat mineral soil mix than in LFH mineral soil mix regardless of season (Figure 2.6). Weekly mean soil volumetric water content in LFH mineral soil mix was 0.00 to 0.36 m^3/m^3 throughout the study, with the lowest weekly mean in LFH mineral soil mix control. LFH mineral soil mix controls were the only treatments with volumetric water contents at 0.00 m^3/m^3. These values occurred throughout December 2009 and January 2010, one week each in June and July 2007 and throughout January and February 2012. These values are seasonal in nature and indicate either frozen soil water conditions in the winter or periods of extreme dryness and water deficits in summer. Weekly mean soil volumetric water content in peat mineral soil mix was 0.07 to 0.62 m^3/m^3 throughout the study.

Weekly mean soil volumetric water content range is the difference between the mean high and the mean low soil volumetric water content within a week (Figure 2.7). Mean soil volumetric water content ranges were greater in peat mineral soil mix than LFH mineral soil mix.

Weekly extreme soil volumetric water content range is the difference between the lowest and the highest volumetric water content within a given week (Figure 2.8). Extreme soil volumetric water content ranges showed a pronounced effect between peat mineral soil mix and LFH mineral soil mix; the range was greater in peat mineral soil mix than in LFH mineral soil mix. The highest ranges in weekly volumetric water content were in peat mineral soil mix, with the highest being 0.55 m^3/m^3. The greatest fluctuations were in peat mineral soil mix *Populus tremuloides* small woody debris and lowest fluctuations were in peat mineral soil mix *Populus tremuloides* large woody debris. The lowest extreme range in weekly volumetric water content was in LFH mineral soil mix *Populus tremuloides* large woody debris. There was no trend with woody debris type or size classes. There was no trend showing either increasing or decreasing soil volumetric water content in relation to soil cover type, woody debris type or size class over time.

Soil volumetric water content was not affected by the same woody debris type and size class factors that contributed to differences in soil temperature. Soil cover type mainly contributed to differences in volumetric water content. Peat mineral soil mix had higher daily, weekly and monthly means and greater fluctuations in soil water content than LFH mineral soil mix. These results are likely due to inherent physical properties of the peat source material. Peat generally has higher organic matter and organic carbon content than LFH and a low bulk density of 0.06 to 0.18 Mg/m^3 compared to 0.10 Mg/m^3 for LFH. High organic matter and organic carbon are directly correlated with increased soil water retention (Hollis et al. 1976, Ohu et al. 1987, Rawls et al. 2003). Higher organic matter and lower bulk density soils are associated with increased pore space and higher water retention capacities associated with capillary action. Lower fluctuations in volumetric water content with LFH mineral soil mix suggests volumetric water content is more stable in LFH mineral soil mix than in peat mineral soil mix.

There was no clear trend in soil volumetric water content over time, indicating that management practices may be able to rely on dependable and consistent properties of source soil material throughout initial stages of reclamation. It may be other contributing factors that affect water content in peat mineral soil mix and LFH mineral soil mix, such as woody debris decomposition that triggers nutrient cycling, thereby increasing organic matter and organic carbon content.

5. CONCLUSIONS

Soil chemical and physical properties were often significantly affected by soil cover type. Woody debris type and size class did not impact soil chemical and physical properties as much as soil cover type did. LFH mineral soil mix had significantly higher silt content, available phosphorus, available potassium and C:N ratio than peat mineral soil mix. Peat mineral soil mix had significantly higher clay content, total inorganic carbon, available sulfate, pH, sodium adsorption ratio and electrical conductivity than LFH mineral soil mix. Available potassium, C:N ratio, electrical conductivity, sodium adsorption ratio and available sulfate significantly changed from 2009 to 2011, depending on the soil cover type. Significant differences in several chemical and physical soil properties are attributed to source parent material and proportions of mixed LFH and peat layers with mineral horizons salvaged below.

Woody debris type and size class moderated soil surface temperature throughout the study. In years one and two following application of woody debris, ranges in daily, weekly and monthly soil temperatures were significantly greater under small woody debris and controls than large woody debris, with fluctuations decreasing in years three, four and five. Soil cover type played an important role in moderating soil volumetric water content. Peat mineral soil mix had higher daily, weekly and monthly means and greater mean and extreme fluctuations in soil water content than LFH mineral soil mix.

Thus reclamation soil cover mixes can influence soil properties and subsequently the succession of ecosystem recovery. Therefore, reclamation areas should be managed based on potential site conditions associated with various soil cover mixes chosen for the intended end land use. The overall effects of woody debris may start out very positive and then its influence may decrease in the early stages of reclamation, as its role begins to interact with that of the surrounding vegetation. However, its use continues to stabilize soil surface temperatures and site conditions and is essential to early ecosystem regeneration. Little decomposition of woody debris is likely occurring in year four after its application, but as reclamation continues and woody debris decay reaches mid to advanced stages, effects of woody debris will likely have an accelerating influence on soil nutrient cycling processes with inputs of nutrients to the soil.

Figure 2.1. Oil sands deposits and surface mineable area in north eastern Alberta, Canada (Government of Alberta 2013).

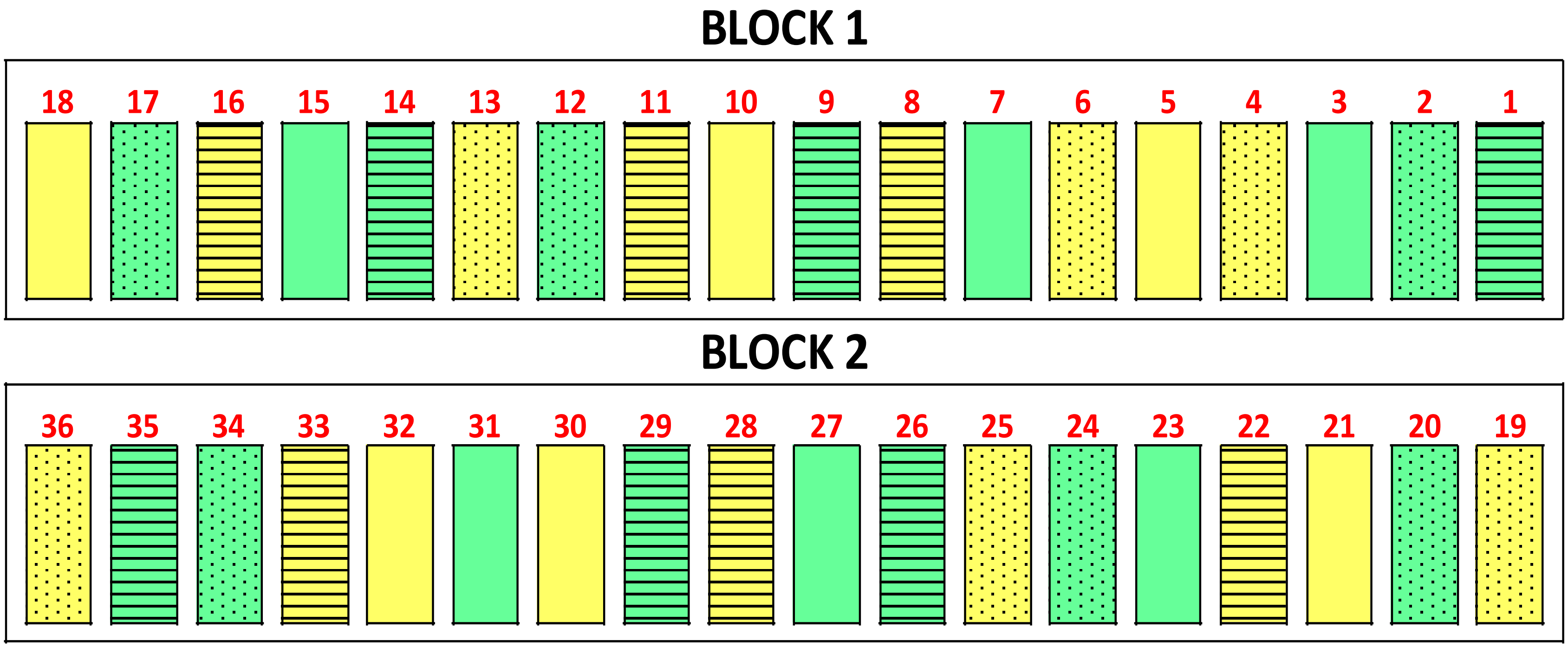

Figure 2.2. Plots on the southeast dump at Suncor Energy Inc. Yellow plots have LFH mineral soil mix cover and green plots have peat mineral soil mix cover. Plots without lines or dots are control plots, plots with dots have *Populus tremuloides* mixed wood woody debris and plots with horizontal lines have *Picea mariana* woody debris (Brown 2010).

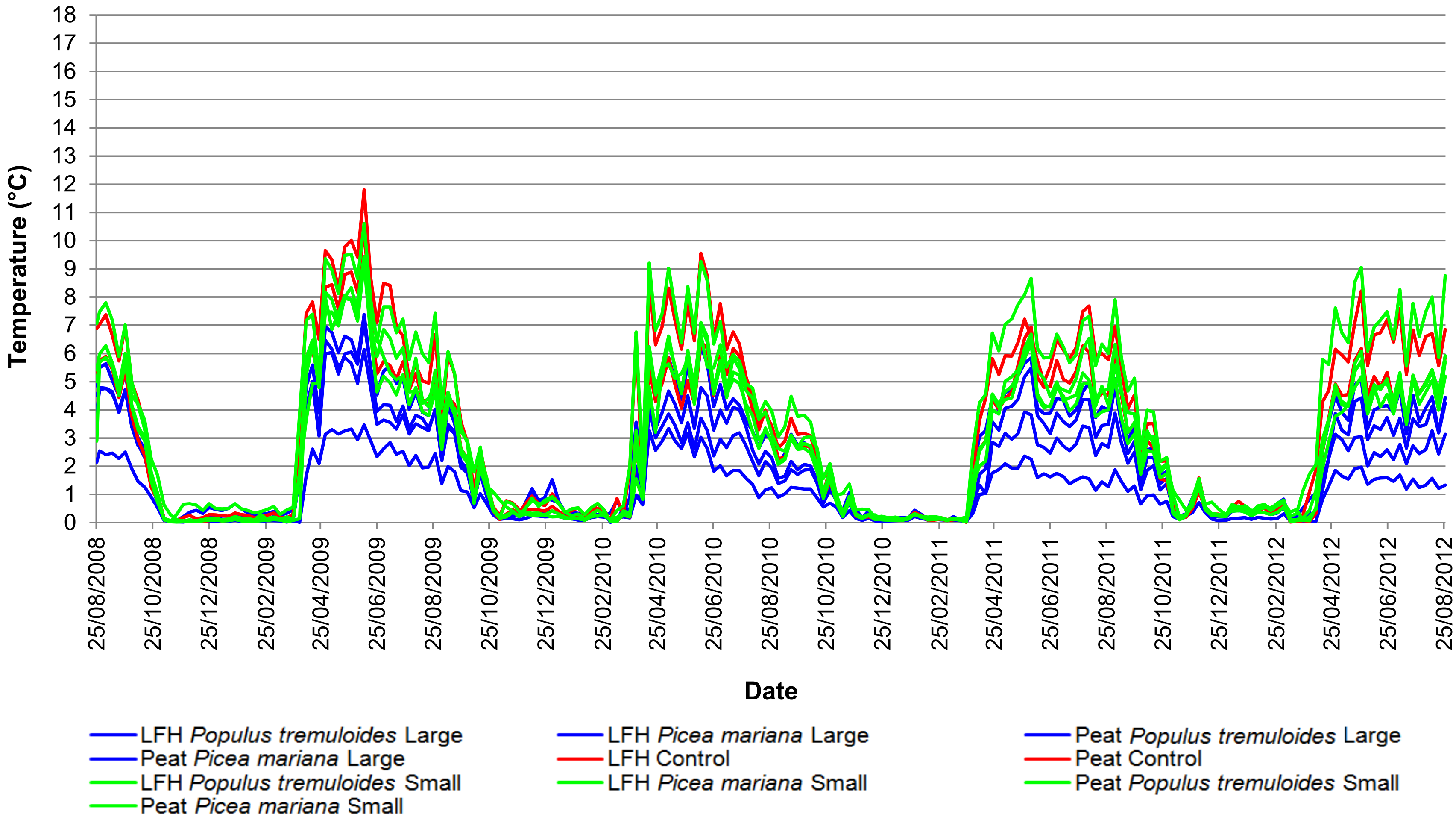

Figure 2.3. Weekly mean soil temperature ranges 2008-2012. Temperature range is the difference between the mean high and mean low values within a week. Graph lines are color coded based on woody debris size classes within woody debris and soil cover types. Large size classes are blue, small size classes are green and controls with no woody debris are red.

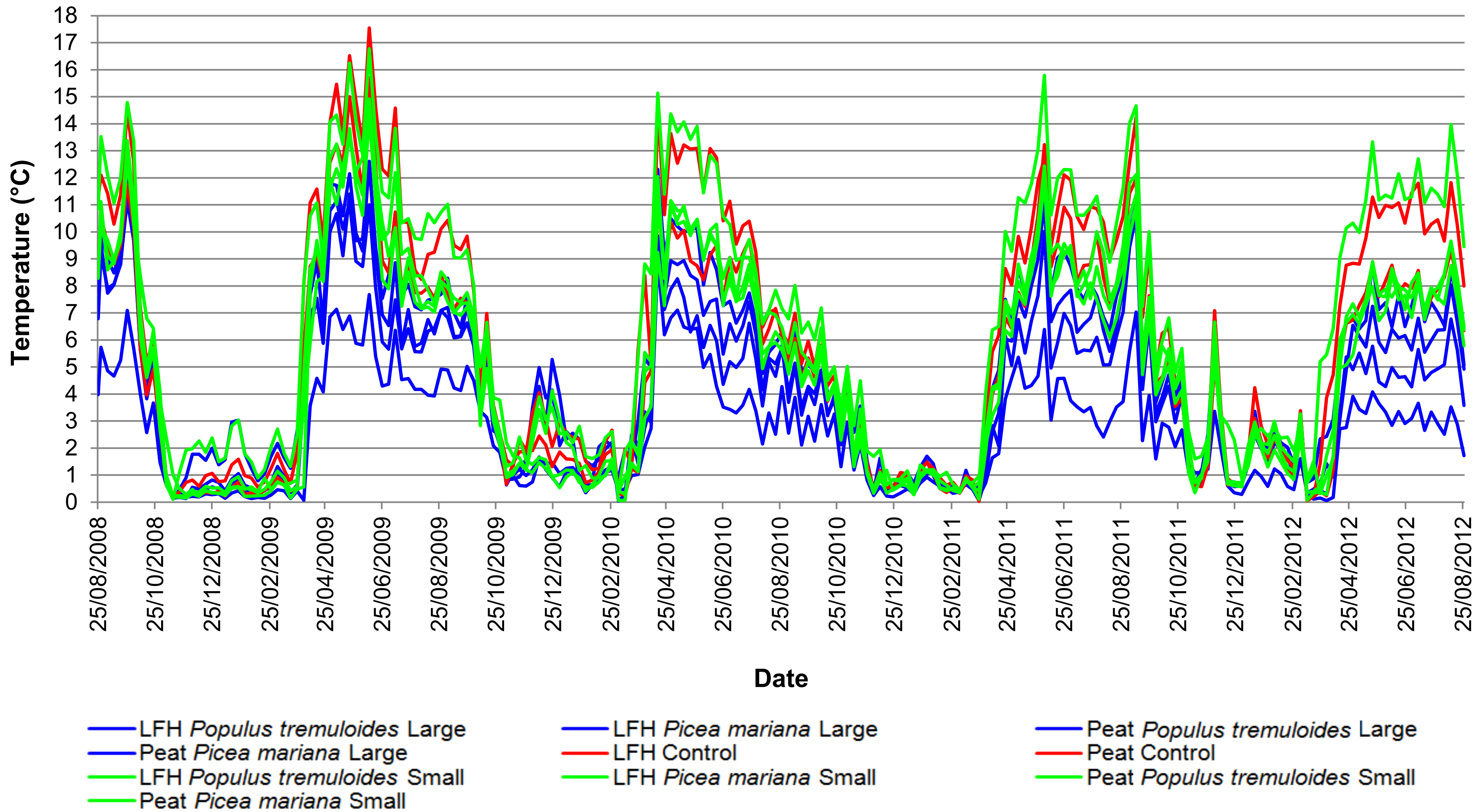

Figure 2.4. Weekly extreme soil temperature ranges 2008-2012. Temperature range is the difference between the lowest and highest values within a week. Graph lines are color coded based on woody debris size classes within woody debris and soil cover types. Large size classes are blue, small size classes are green and controls with no woody debris are red.

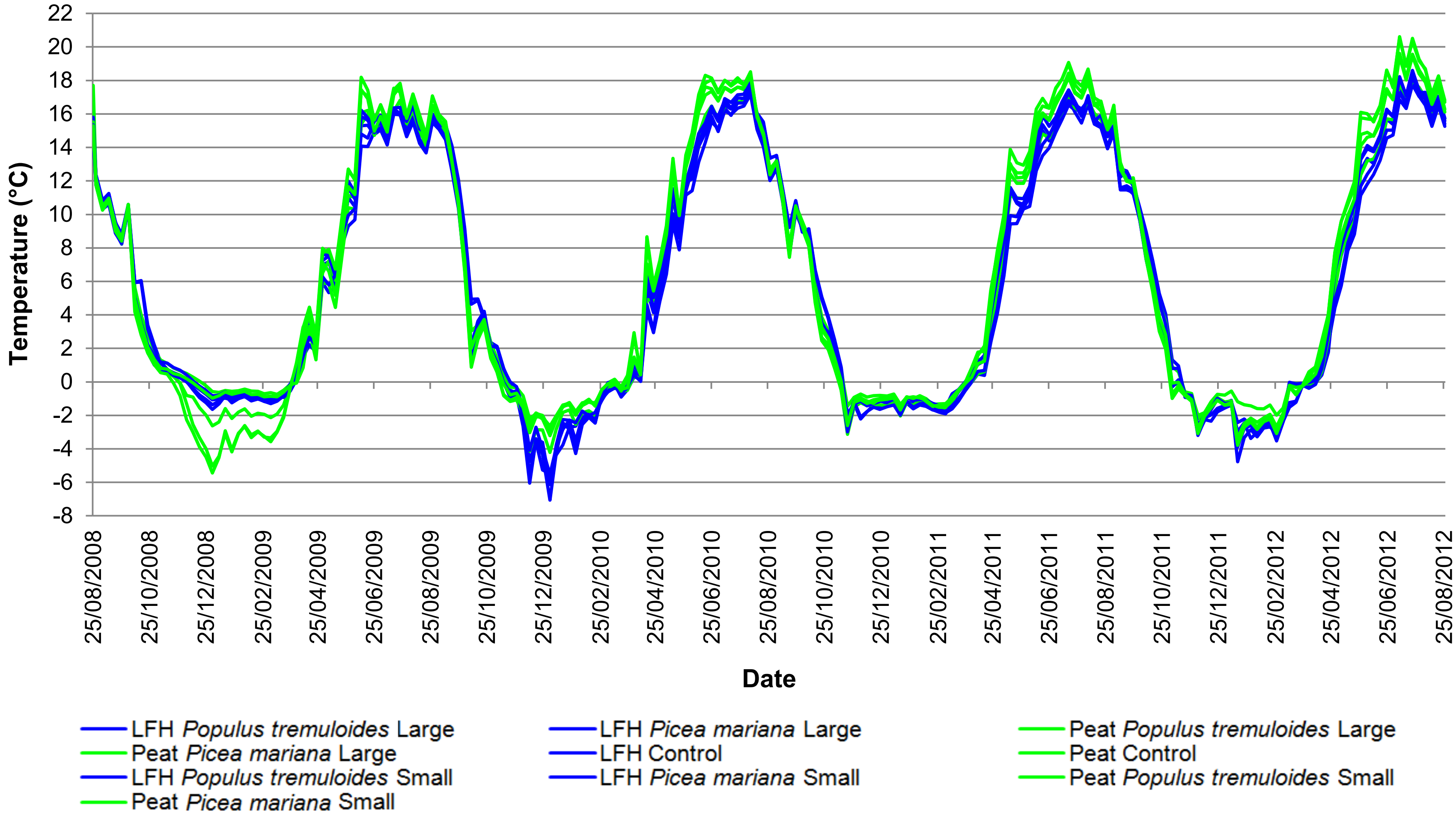

Figure 2.5. Weekly soil temperature means 2008-2012. Temperature mean is the mean value within a week. Graph lines are color coded based on soil cover type LFH mineral soil mix is blue and peat mineral soil mix is green.

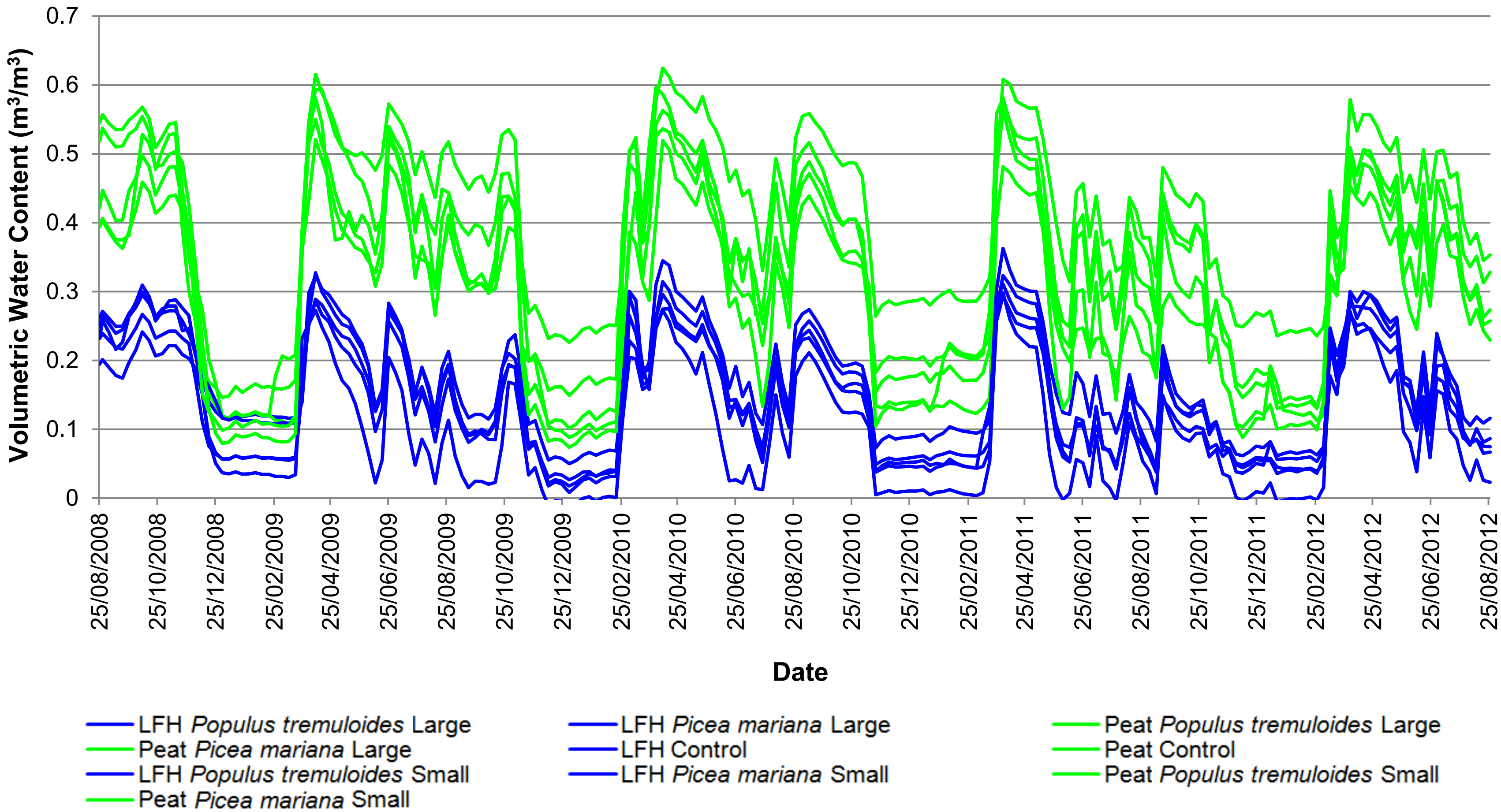

Figure 2.6. Weekly soil volumetric water content means 2008-2012. Volumetric water content is the mean value within a week. Graph lines are color coded based on soil cover type LFH mineral soil mix is blue and peat mineral soil mix is green.

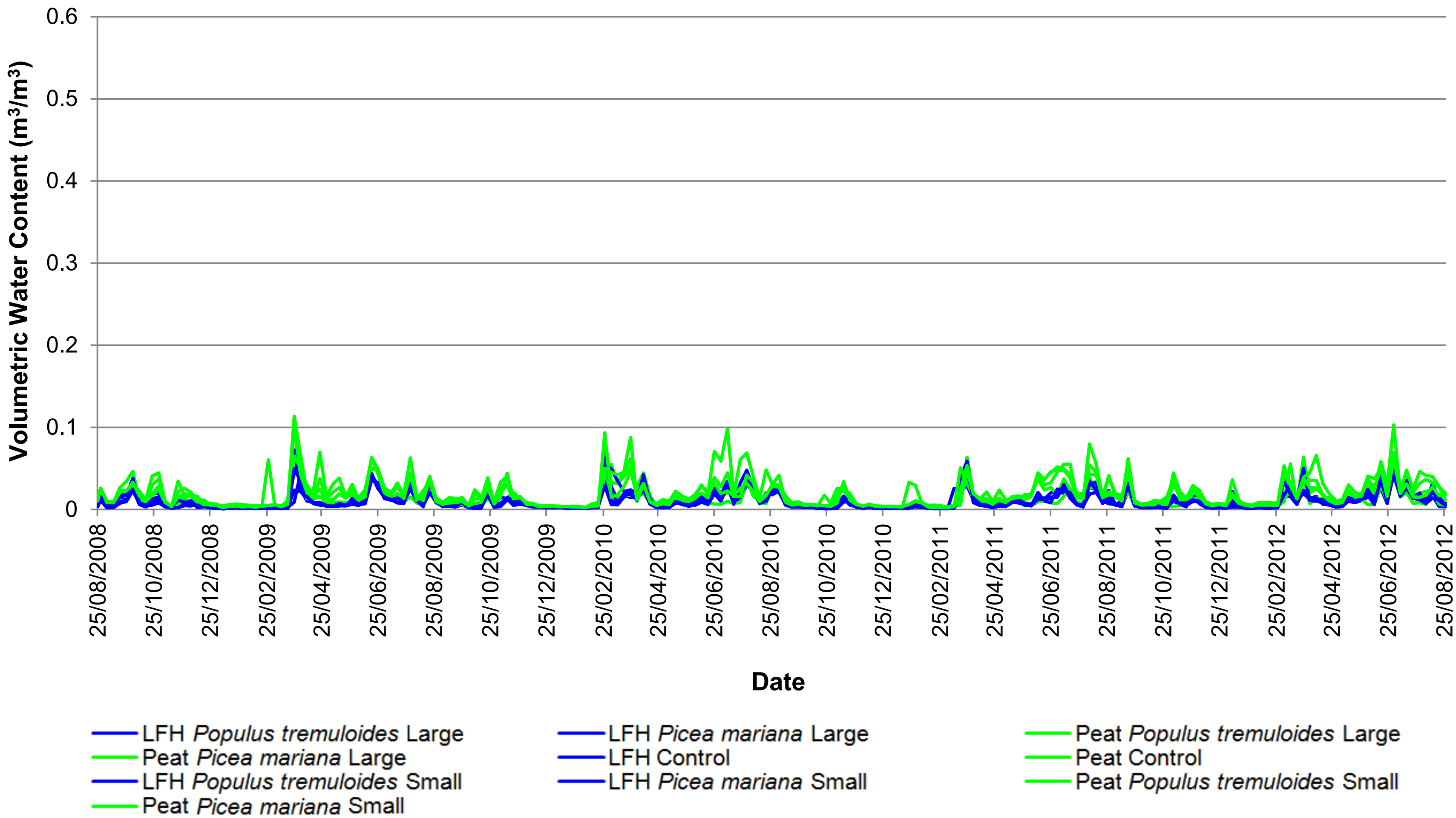

Figure 2.7. Weekly mean soil volumetric water content ranges 2008-2012. Volumetric water content range is the difference between the mean high and the mean low values within a week. Graph lines are color coded based on soil cover type LFH mineral soil mix is blue and peat mineral soil mix is green.

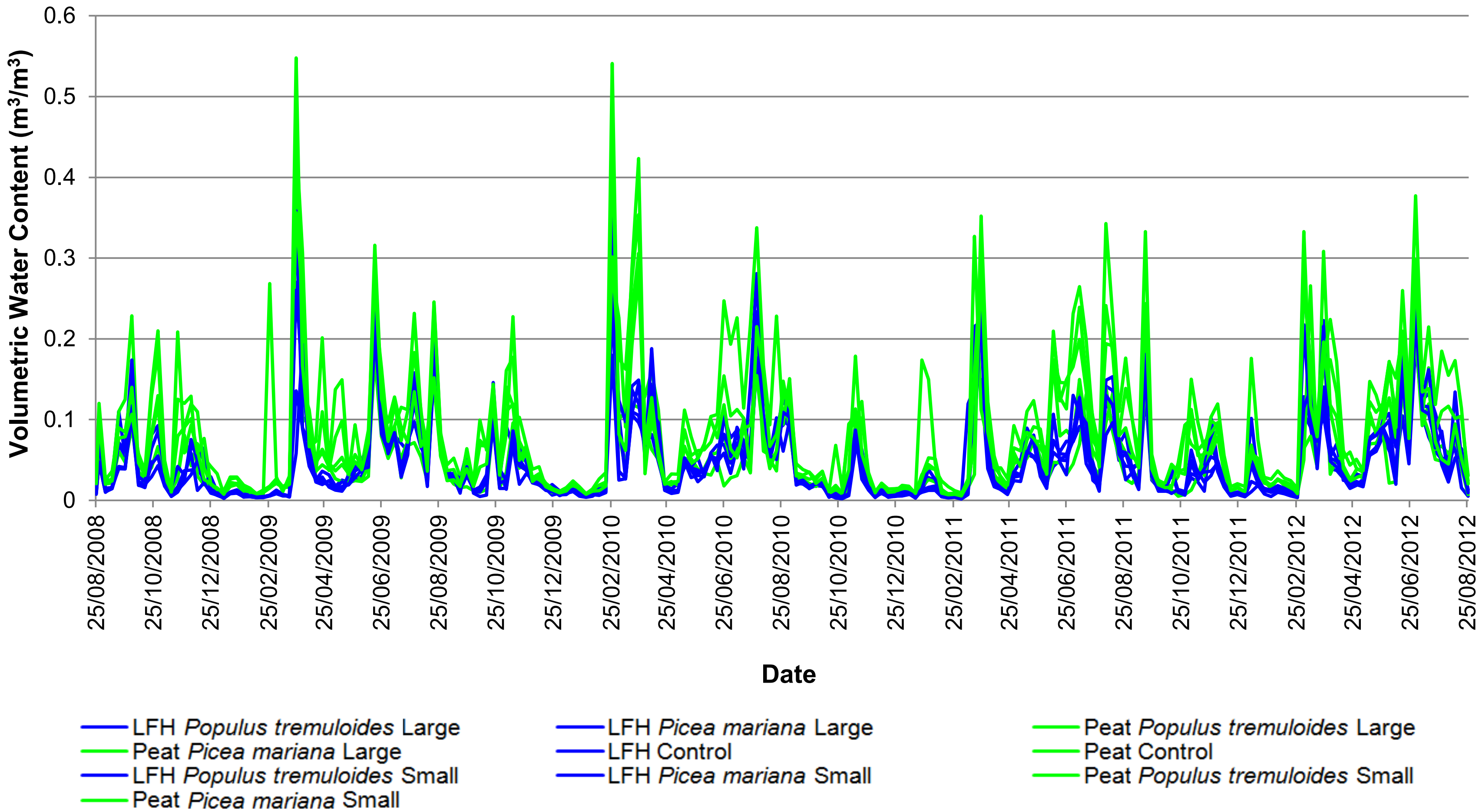

Figure 2.8. Weekly extreme soil volumetric water content ranges 2008-2012. Volumetric water content range is the difference between the lowest and highest values within a week. Graph lines are color coded based on soil cover type LFH mineral soil mix is blue and peat mineral soil mix is green.

Table 2.1. Mean chemical and physical soil properties in 2011 by soil cover type.

Parameter	Unit	LFH Mineral Soil Mix	Peat Mineral Soil Mix
Available nitrate	mg/kg	<2.0 (0.0)	<2.0 (0.0)
Available ammonium	mg/kg	1.21 (0.20)	0.39 (0.03)
Available phosphorus	mg/kg	35.7 (2.7)[a]	14.0 (2.0)[b]
Available potassium	mg/kg	227.9 (33.3)[a]	120.6 (10.5)[b]
Available sulfate	mg/kg	90.7 (34.3)[b]	201.1 (25.2)[a]
C:N ratio		33.1 (0.7)[a]	31.3 (0.4)[b]
Total organic carbon	%	7.34 (1.30)	6.62 (0.50)
Total inorganic carbon	%	0.29 (0.10)[b]	0.76 (0.04)[a]
Total nitrogen	%	0.24 (0.04)	0.23 (0.02)
Hydrogen ion activity	pH	6.4 (0.1)[b]	7.4 (0.0)[a]
Electrical conductivity	dS/m	1.1 (0.2)[b]	1.7 (0.1)[a]
Sodium adsorption ratio		0.6 (0.1)[b]	1.1 (0.1)[a]
Sand	%	51.4 (1.0)	50.1 (0.9)
Silt	%	35.7 (0.6)[a]	31.5 (0.6)[b]
Clay	%	12.9 (0.6)[b]	18.4 (0.4)[a]
Bulk density	Mg/m^3	0.82 (0.06)	0.89 (0.04)

Numbers are means followed by standard errors in brackets, $n = 18$.
Different letters denote significance between soil cover types at $p < 0.05$.
Most available nitrogen or available ammonium values were below detection limits; therefore, no statistical analysis was conducted.

Table 2.2. Mean chemical and physical soil properties over three growing seasons by soil cover type.

Parameter	Unit	August 2008		August 2009		August 2011	
		LFH Mineral Soil Mix	Peat Mineral Soil Mix	LFH Mineral Soil Mix	Peat Mineral Soil Mix	LFH Mineral Soil Mix	Peat Mineral Soil Mix
Available nitrate	mg/kg	4.5 (0.8)	6.1 (0.9)	2.0 (0.0)	2.2 (0.2)	<2.0 (0.0)	<2.0 (0.0)
Available ammonium	mg/kg	1.00 (0.10)^{A}	<0.30^{B}	-	-	1.21 (0.20)	0.39 (0.03)
Available phosphorus	mg/kg	21.3 (1.3)^{A}	7.1 (0.8)^{B}	32.4 (2.2)^{A}	16.0 (1.8)^{B}	35.7 (2.7)^{A}	14.0 (2.0)^{B}
Available potassium	mg/kg	-	-	137.0 (13.1)$^{A/b}$	97.0 (6.8)$^{B/b}$	227.9 (33.3)$^{A/a}$	120.6 (10.5)$^{B/a}$
Available sulfate	mg/kg	-	-	31.3 (8.8)$^{B/b}$	133.3 (14.0)^{A}	90.7 (34.3)$^{B/a}$	201.1 (25.2)^{A}
C:N ratio		23.8 (1.6)^{A}	26.8 (0.3)^{A}	26.8 (0.4)$^{A/b}$	23.8 (0.6)$^{B/b}$	33.1 (0.7)$^{A/a}$	31.3 (0.4)$^{B/a}$
Total organic carbon	%	5.27 (0.60)^{B}	7.27 (0.54)^{A}	5.93 (0.74)	6.35 (0.49)	7.34 (1.30)	6.62 (0.50)
Total nitrogen	%	0.39 (0.12)^{A}	0.27 (0.02)^{A}	0.22 (0.03)^{B}	0.27 (0.02)^{A}	0.24 (0.04)	0.23 (0.02)
Hydrogen ion activity	pH	-	-	6.4 (0.1)^{B}	7.5 (0.0)^{A}	6.4 (0.1)^{B}	7.4 (0.0)^{A}
Electrical conductivity	dS/m	-	-	0.58 (0.1)$^{B/b}$	1.24 (0.1)$^{A/b}$	1.1 (0.2)$^{B/a}$	1.7 (0.1)$^{A/a}$
Sodium adsorption ratio		-	-	0.3 (0.0)$^{B/b}$	0.6 (0.1)$^{A/b}$	0.6 (0.1)$^{B/a}$	1.1 (0.1)$^{A/a}$
Sand	%	-	-	53.3 (0.8)	51.4 (0.8)	51.4 (1.0)	50.1 (0.9)
Silt	%	-	-	34.4 (0.7)^{A}	29.8 (0.9)^{B}	35.7 (0.6)^{A}	31.5 (0.6)^{B}
Clay	%	-	-	12.3 (0.7)^{B}	18.7 (0.3)^{A}	12.9 (0.6)^{B}	18.4 (0.4)^{A}

Numbers are means followed by standard errors in brackets, $n = 18$.
Upper case letters indicate significant differences between soil covers of the same year and lower case letters indicate significant differences between years of the corresponding soil cover at $p < 0.05$ for parametric tests and $p < 0.1$ for non parametric tests.
Available ammonium, available nitrate, clay, sand, silt, total nitrogen and total organic carbon were not analyzed among years.
Most available nitrogen or available ammonium values were below detection limits.
Data from 2008 was not analyzed for comparison with data from 2011.
2008 and 2009 data from Brown (2010).

Table 2.3. Mean chemical and physical soil properties in 2011 for LFH mineral soil mix by woody debris type and size class.

Parameter	Unit	*Populus tremuloides* Large	*Populus tremuloides* Small	*Picea mariana* Large	*Picea mariana* Small	Control
Available nitrate	mg/kg	<2.0 (0.0)	<2.0 (0.0)	<2.0 (0.0)	<2.0 (0.0)	<2.0 (0.0)
Available ammonium	mg/kg	1.85 (1.80)	1.05 (0.60)	0.63 (0.50)	1.07 (0.60)	1.35 (1.40)
Available phosphorus	mg/kg	35.0 (6.3)	36.7 (4.8)	28.5 (5.9)	47.0 (6.0)	33.5 (5.4)
Available potassium	mg/kg	261.7 (74.2)	205.2 (40.7)	159.2 (41.9)	293.8 (89.9)	223.7 (65.5)
Available sulfate	mg/kg	98.7 (59.1)	39.2 (10.3)	40.2 (11.9)	106.3 (68.9)	129.8 (96.4)
C:N ratio		31.5 (0.7)	30.7 (0.7)	32.2 (1.0)	30.6 (0.9)	31.4 (0.6)
Total organic carbon	%	6.59 (1.60)	5.37 (1.00)	7.56 (2.50)	8.59 (3.20)	7.96 (2.50)
Total inorganic carbon	%	0.16 (0.06)	0.12 (0.04)	0.74 (0.60)	0.32 (0.20)	0.21 (0.07)
Total nitrogen	%	0.22 (0.06)	0.18 (0.03)	0.26 (0.09)	0.29 (0.10)	0.26 (0.09)
Hydrogen ion activity	pH	6.4 (0.2)	6.4 (0.2)	6.5 (0.2)	6.4 (0.2)	6.3 (0.2)
Electrical conductivity	dS/m	1.2 (0.2)	1.0 (0.1)	0.8 (0.1)	1.2 (0.3)	1.2 (0.4)
Sodium adsorption ratio		0.5 (0.1)	0.5 (0.0)	0.4 (0.0)	0.5 (0.1)	0.9 (0.4)
Sand	%	51.7 (2.2)	52.4 (2.0)	52.3 (1.6)	50.6 (1.7)	50.8 (1.6)
Silt	%	36.3 (1.5)	34.7 (1.4)	34.7 (1.0)	36.7 (1.3)	35.9 (0.8)
Clay	%	12.0 (1.2)	12.9 (1.5)	13.0 (1.0)	12.7 (0.9)	13.3 (1.0)
Texture		L-SL	L-SL	L-SL	L-SL	L-SL
Bulk density	Mg/m^3	0.88 (0.10)	0.87 (0.07)	0.86 (0.10)	0.82 (0.10)	0.75 (0.10)

Numbers are means followed by standard errors in brackets, n = 6.
Most available nitrogen or available ammonium values were below detection limits.

Table 2.4. Mean soil chemical and physical properties in 2011 in peat mineral soil mix soil by woody debris type and size class.

Parameter	Unit	*Populus tremuloides* Large	*Populus tremuloides* Small	*Picea mariana* Large	*Picea mariana* Small	Control
Available nitrate	mg/kg	<2.0 (0.0)	2.0 (0.0)	<2.0 (0.0)	<2.0 (0.0)	<2.0 (0.0)
Available ammonium	mg/kg	0.40 (0.10)	0.35 (0.05)	0.37 (0.05)	0.37 (0.05)	0.45 (0.20)
Available phosphorus	mg/kg	11.3 (3.2)	14.5 (2.4)	13.0 (3.0)	15.7 (1.8)	14.8 (5.5)
Available potassium	mg/kg	123.7 (26.7)	123.0 (11.3)	109.7 (8.1)	125.0 (8.3)	121.0 (27.7)
Available sulfate	mg/kg	143.8 (35.8)	235.7 (49.9)	149.8 (40.7)	179.5 (58.1)	249.0 (53.8)
C:N ratio		33.4 (1.3)	31.1 (0.9)	34.6 (1.9)	34.3 (0.8)	32.6 (1.3)
Total organic carbon	%	7.12 (1.40)	6.45 (0.70)	7.00 (1.20)	6.06 (0.80)	6.55 (0.80)
Total inorganic carbon	%	0.83 (0.04)	0.78 (0.04)	0.82 (0.04)	0.80 (0.04)	0.67 (0.10)
Total nitrogen	%	0.25 (0.05)	0.24 (0.03)	0.24 (0.05)	0.20 (0.02)	0.22 (0.02)
Hydrogen ion activity	pH	7.5 (0.1)	7.4 (0.0)	7.5 (0.0)	7.5 (0.0)	7.4 (0.1)
Electrical conductivity	dS/m	1.5 (0.2)	1.9 (0.2)	1.4 (0.3)	1.7 (0.2)	2.0 (0.2)
Sodium adsorption ratio		0.9 (0.2)	1.0 (0.2)	1.0 (0.2)	1.0 (0.2)	1.3 (0.3)
Sand	%	50.1 (2.5)	48.5 (2.1)	49.8 (1.8)	50.3 (1.4)	51.0 (0.3)
Silt	%	30.8 (1.8)	32.9 (1.3)	32.0 (1.2)	30.9 (1.3)	31.1 (0.8)
Clay	%	19.2 (0.9)	18.6 (1.0)	18.2 (1.0)	18.7 (0.4)	17.9 (0.7)
Texture		L-SL	L-SL	L-SL	L-SL	L-SL
Bulk density	Mg/m^3	0.90 (0.09)	1.04 (0.10)	0.89 (0.10)	0.88 (0.09)	0.81 (0.04)

Numbers are means followed by standard errors in brackets, n = 6.
Most available nitrogen or available ammonium values were below detection limits.

CHAPTER III. WOODY DEBRIS AND SOIL COVER TYPE IMPACTS ON VEGETATION AFTER OIL SANDS MINE RECLAMATION

1. INTRODUCTION

Woody debris is any type of dead woody material and is a critical component of forest ecosystems around the world. Woody debris contributes to plant community structure, productivity, microhabitat diversity, water retention, erosion control, nutrient and mineral cycling, energy fluxes and soil formation processes (Harmon et al. 1986, Rambo and Muir 1998, Hély et al. 2000, Ódor and Standovár 2001, Rambo 2001, Shorohova and Shorohov 2001, Ódor et al. 2006, Brown 2010, Brown and Naeth 2014). Woody debris inputs in the Boreal Forest Natural Region contribute to successional processes of multi-directional, dynamic forest ecosystems (Finegan 1984, McCook 1994, Cook 1996, Mackenzie 2006). The ecological value woody debris provides to these sustainable ecosystems is of particular interest for reclamation of disturbed boreal forests.

Approximately 767 km^2 of land in Alberta have been disturbed by oil sands mining (Government of Alberta 2013), with the majority of this disturbed area occurring in the Boreal Forest Natural Region. Reclamation of open pit mines began at Suncor Energy Inc. in 1971 (Brown 2010). Since then, 104 ha have been certified reclaimed, with an additional 5,042 ha permanently reclaimed, but not certified (Government of Alberta 2013). The goal of oil sands mine reclamation is to reclaim disturbed areas to equivalent land capability of what existed prior to an activity (Alberta Environment 2010a). This presents a challenge to develop sustainable reclaimed systems on a large scale, with available material.

Two main components of reclamation that influence development of sustainable ecosystems include topsoil placement and revegetation. Two materials used for topsoiling include peat mineral soil mix and LFH mineral soil mix, which is also known as upland surface soil or forest floor mineral mix (Naeth et al. 2013). Peat mineral soil mix was historically used because of its availability; however, LFH mineral soil mix provides a superior growth medium for plants relative to peat mineral soil mix (MacMillan et al. 2006, Mackenzie 2006, Mackenzie and Naeth 2010, Brown 2010, Hahn 2012, Mackenzie and Quideau 2012, Mackenzie 2012, Brown and Naeth 2014). LFH mineral soil mix is a rich source of organic matter, macro and micronutrients and has a carbon to nitrogen (C:N) ratio and pH comparable to undisturbed upland forests (Alberta Environment and Water 2012). Ecosystem recovery with LFH mineral soil mix cover promotes rapid revegetation with native, favourable and desirable species that comprises a sustainable reclaimed ecosystem in disturbed oil sands mining areas.

Other methods to expedite ecosystem recovery after oil sands mining usually involve materials available at the time of reclamation. Fertilizer and annual nurse crops have historically been used to stimulate plant growth and control wind and water erosion. Woody debris cleared from neighbouring disturbances is a readily available and economic resource that can facilitate ecosystem recovery and plant community development of large scale disturbances. Historical management of woody debris includes piling and burning and mulching (Government of Alberta 2009). More recent regulations recognize the ecological value of using woody debris and encourage its use in reclamation (ESRD 2013).

Use of woody debris in reclamation is a relatively new area of research, with few studies directly focused on effects of woody debris on ecosystem recovery after disturbance and reclamation. Many mining companies have developed standard woody debris handling practices; however, many of these approaches are based on trial and error applications and have been directed mainly to erosion control. One study directly addressed use of woody debris for reclamation (Brown 2010, Brown and Naeth 2014). However, this study was of short duration and only covered the first two years of effects. Longer term effects of woody debris and soil cover types are expected, particularly as the woody debris begins to decompose and vegetation on the site matures. No field based research has directly examined woody debris volume application rates for reclamation applications. Current best management practices for recommended application rates are based on a review of the literature on natural inputs from woody debris to natural boreal forests (Vinge and Pyper 2013).

2. RESEARCH OBJECTIVES

The overall objective of this research was to evaluate ecological effects of using woody debris as an amendment to facilitate reclamation of disturbed landscapes in the Athabasca Oil Sands Region at years four and five after reclamation. Specific research objectives were as follows.

- Determine the impacts of woody debris and soil cover type on select vegetation properties (canopy cover, ground cover, vascular and non vascular species composition, richness, diversity, woody plant density).
- Determine if the above impacts are affected by woody debris size.
- Determine optimal cover and volume application rates for woody debris.

3. MATERIALS AND METHODS

3.1 Study Area

The research study area is located on the Suncor Energy Inc. (Suncor) oil sands mine, in the Athabasca Oil Sands Region of Alberta, approximately 30 km north of Fort McMurray, Alberta (Figure 2.1). The research site is in the Central Mixed Wood Natural Subregion of the Boreal Forest Natural Region (Natural Regions Committee 2006).

The Boreal Forest Natural Region is characterized by a continental climate with short, warm summers and long, cold winters (Natural Resources Canada 2007). Mean annual temperature for the Fort McMurray area is 0.7 °C, with a mean daily maximum of 23.2 °C in July and a mean daily minimum of -24 °C in January (Environment Canada 2010). Mean annual precipitation is 455.5 mm, with 342.2 mm falling as rain and 155.8 cm falling as snow. On average there are approximately 97 frost free days (Natural Regions Committee 2006).

Topography of the Central Mixed Wood Natural Subregion consists mainly of gently undulating plains with minor inclusions of hummocky uplands (Natural Regions Committee 2006). The underlying bedrock is composed of Cretaceous shales with minor inclusions of sandstones and siltstones in the south and minor inclusions of Devonian limestones, shales and siltstones in the northeast. Bedrock geology is generally of the McMurray and Clearwater formations. Parent materials include coarse to fine textured tills, fine textured glaciolacustrine deposits, coarse textured fluvial and eolian deposits and organic deposits. Gray Luvisols dominate the upland soils, with Dystric and Eutric Brunisols associated with coarse textured soils. Peatland and wetland soils are dominated by organic Mesisols and minor Fibrisols, Cryosols and Orthic and peaty Gleysols.

Vegetation of the Central Mixed Wood Natural Subregion consists of upland forests and lowland peatlands. Upland forests are dominated by *Picea glauca* (Moench) Voss (white spruce), *Populus tremuloides* Michx. (trembling aspen) and mixed stands on fine textured soils (Natural Regions Committee 2006, Natural Resources Canada 2007). *Abies balsamea* (L.) Mill. (balsam fir), *Betula papyrifera* Marsh. (paper birch), *Populus balsamifera* L. (balsam poplar) and *Pinus banksiana* Lamb. (jack pine) occur in upland forests, with *Pinus banksiana* forests dominating coarse textured soils. Peatlands and wetlands cover almost half the study area and are dominated by *Larix laricina* (Du Roi) K. Koch (tamarack) and *Picea mariana* (P. Mill.) B.S.P. (black spruce) fens and bogs.

3.2 Research Site Location And Construction

The research site is located on the southeast dump (SE dump) of Suncor Energy Inc., occupying an area of 70 by 300 m on a mid slope, with a southeast facing aspect (Brown 2010). The site was cleared in 1999 and used as a dump for saline sodic overburden waste until 2004. Research plot construction began in November 2007 and was completed in February 2008.

Plot construction was done on an operational scale and involved soil cover placement, followed by woody debris application from November 22 to December 2, 2007. Additional woody debris was salvaged and placed from February 12 to 14, 2008. All woody debris was salvaged from a nearby area, then directly placed without any stockpiling time. A 100 cm cap of clean overburden separated treatments from saline sodic overburden. LFH mineral soil mix was salvaged to 20 cm, stockpiled 3 months and applied at 20 cm over 30 cm of B and C horizon mixed subsoil. LFH mineral soil mix was salvaged from mesic (b and d) ecosites with *Populus tremuloides*, *Picea glauca* and *Pinus banksiana* (Archibald 2014); no material properties information from the LFH donor site was obtained. Peat mineral soil mix was applied at 30 cm on clean overburden; no material properties from the donor site or stockpile information on peat mineral soil mix were obtained. Materials were spread with a D6 Caterpillar bulldozer and woody debris was placed using a grapple hoe. Plots were aerially fertilized in June 2008 with 23.5:25:8 (nitrogen:phosphorus:potassium) fertilizer at 300 kg/ha and in August 2009 with a 31.5:16:5 fertilizer at 250 kg/ha with a fixed wing aircraft (Brown 2010). They were again aerially fertilized in June 2010 and 2011 using granular urea 46:0:0, monoammonium phosphate 11:52:0 and muriate of potash 0:0:60 fertilizers.

Meteorological conditions in the study area varied from plot construction to the end of the study in 2012 (Appendix B). In year one of the study accumulated precipitation was similar to long term normals; years two (2009) and four (2011) were substantially drier. Year five (2012) was wetter than long term normals by over 50 mm. Temperature differences between years varied seasonally relative to long term normals. June, July and August air temperatures were higher than long term normals in all years. 2010 had the highest yearly temperature mean, followed by 2011 and 2012. 2008 and 2009 were more than 1 °C cooler than all other years.

3.3 Experimental Design

Six research treatment combinations consisted of no woody debris or woody debris from *Picea mariana* or *Populus tremuloides* mixed wood forests placed on LFH mineral soil mix and peat mineral soil mix covered substrates. Woody debris treatments, including controls with no woody debris are hereafter referred to as woody debris type; LFH mineral soil mix and peat mineral soil mix covered substrates are hereafter referred to as soil cover type. Two rows of plots were horizontally placed along a slope in a complete randomized block design. Each block was 10 m wide by 30 m long (Figure 2.2) and each row had three replicates of each treatment for a total of 36 treatment plots. A 5 m buffer separated plots and a 10 m buffer separated rows. Slopes in the bottom row (6 to 11 %) were steeper than in the top row (2 to 8 %). Half the plots had LFH mineral soil mix applied at a depth of 20 cm, over 30 cm of B and C mix horizon subsoil and 100 cm of clean overburden. The other half had peat mineral soil mix applied at a depth of 30 cm, over 100 cm of clean overburden.

For each soil cover type, six plots had *Picea mariana* woody debris, six had *Populus tremuloides* mixed wood woody debris and six were controls with no woody debris (Figure 2.2). *Populus tremuloides* mixed woody debris contained approximately 70 % *Populus tremuloides*, 30 % *Picea glauca* and traces of *Betula papyrifera* (Brown 2010). All debris was arranged in a vertical direction (down slope) in plots and placed to provide maximum contact with the soil surface. Mean woody debris cover for *Populus tremuloides* mixed wood treatments after construction was 11 %; *Picea mariana* treatments mean was 20 % due to greater abundance of small and fine sized woody debris. Woody debris size classes were fine woody debris with diameter less than 2 cm, small woody debris with diameter 2 to 5 cm, medium woody debris with diameter 5 to 15 cm and large woody debris with diameter greater than 15 cm.

3.4 Vegetation Assessment

Vegetation was assessed in July 2011 and August 2012 using two types of assessments. One assessment examined 1 m^2 permanent quadrats established in each plot after site construction in 2008. The second assessment examined four quadrats established in each plot in 2011 for size class assessments and are discussed in section 3.5. For permanent quadrat assessments, 15 quadrats were placed in five rows running from the top of each plot to the bottom, with three quadrats evenly spaced across the plot within each row. In 2011, seven of the 15 permanent quadrats in each plot were randomly selected from the first, third and fifth rows for vegetation assessments. Number of quadrats per plot were based on historical sampling and species area curves. All 15 permanent quadrats in each plot were assessed in 2012.

In each quadrat, ground cover (%) was estimated for live vegetation, bare ground, rock, litter and woody debris by size class. Litter included all dead vegetation and bark fragments from the woody debris. Canopy cover (%) of vegetation by species was determined for all growth forms (trees, shrubs, forbs, graminoids, bryophytes, lichens). Vegetation canopy levels were accounted for, including woody debris that was overlapped by vegetation, thus total cover could exceed 100 %. Cover was estimated in 0.5 % increments and values less than 0.5 % were recorded as trace. Only vegetation rooted inside quadrats and runners of *Fragaria* spp. (strawberry) growing in the quadrat were included.

Woody plant density was assessed by counting the number of individual plants or stems in each quadrat for each species of tree and shrub growth forms. Some species were difficult to assess due to multiple stems per plant, such as *Rubus idaeus* L. (wild red raspberry). *Rubus ideaus* density was determined by counting a clump of stems emerging from one location as a single plant, since multiple stems can emerge from the same spot.

Following vegetation assessments, systematic walk through surveys were conducted along three to five vertical transects through each plot, with the assessor scanning 1 to 3 m on each side. Species that had not been found in the quadrats were recorded each time they were found for species frequency.

Vascular and non vascular species were identified to genus and species if possible. Field identification was according to Johnson et al. (1995) with nomenclature according to the Flora of North America Editorial Committee (1993) and the Alberta Conservation Information Management System database (ACIMS 2013). Classification of native and non native species was based on the United States Department of Agriculture plant database (USDA 2013).

In 2011 and 2012, specimens of species that could not be identified in the field were collected and identified in the laboratory. Vascular specimens were collected and stored in sealed freezer bags and pressed in cardboard and newspaper. In 2011, bryophytes were identified to species. If unidentifiable in the field, specimens were removed to be identified under a microscope in the laboratory. Specimens were dried thoroughly and stored in paper bags.

3.5 Woody Debris Volume, Cover And Size Class Determination

Woody debris volume was assessed in August 2012 by measuring the diameter and length of every large (greater than 15 cm diameter) and medium (5 to 15 cm diameter) piece of woody debris in each plot. A preliminary walk through survey was conducted to assess woody debris distribution. If woody debris distribution was uniform throughout the plot, one half of the plot was assessed and the final volumes were multiplied by two to scale up to the total plot volume.

Volume of woody debris was calculated from the formula for volume of a cylinder (Stokland 2001) and a modified version of Smalian's formula (Province of British Columbia 2010). Length of each piece of woody debris was measured with a measuring tape. Diameter of each piece of woody debris was measured using a caliper near both ends of each woody debris piece and the center of the piece, when the size of the pieced allowed these three measurements; a mean of the three diameters was used in volume calculation. Volume of woody debris pieces was calculated per m^2 as π x (mean diameter/2)^2 x length and then converted to volume per ha. For woody debris pieces that were flattened or not cylindrical in shape, the final volume calculated was reduced or halved based on field notes.

Woody debris size classes were examined in August 2012 as part of the size class assessments. A stratified sampling design was used to establish four quadrats that were randomly placed in each plot in 2011, with one quadrat for each size class of woody debris (fine, small, medium, large). Spruce cones were considered fine woody debris. A 1 m^2 quadrat was used for medium and large size classes and a 0.25 m^2 quadrat for fine and small size classes. For plots lacking woody debris pieces in a size class, an extra quadrat was added to another experimental unit in the same treatment to balance sampling design. The quadrat was placed to maximize the volume of the target woody debris piece. Woody debris volume was assessed in these size class quadrats. These measurements were conducted in the same way as for volumes in the whole plot, but the data were kept separate and used specifically to determine volume size class relationships. Vegetation, ground and woody debris cover was assessed in the size class quadrats in 2012. Data collection was conducted in the same way as for the permanent quadrats in the whole plot.

In 2011 and 2012 woody debris cover was quantified in permanent vegetation quadrats during vegetation assessments by estimating volume and percent cover by size class. Volume was estimated as detailed above. Diameter and length of woody debris pieces that intercepted, but also lay outside the quadrat, were recorded separately for inside and outside quadrat data. Size class of woody debris pieces in quadrats was determined based on their diameter in the quadrat. Therefore, mean diameter may not reflect size class in the quadrat. Exact cover calculated during volume assessments were rounded to the nearest 0.5 for individual quadrats.

3.7 Slope And Aspect Determination

Effects of slope and aspect were visible in vegetation with differences, for example, of more litter and graminoids in some areas. Thus slope and aspect were determined to help explain treatment variability. In each plot, slope was measured with a clinometer and aspect was determined with a compass. Slope position of each plot was assigned based on its location along the transect as upper, mid and lower positions. Slope was recorded from the top center to the bottom center of the plot and aspect from the midpoint center of the plot.

3.8 Vegetation Data Analyses

A mean of plant species cover across quadrats in an experimental unit was used to calculate Shannon index of diversity; natural logs were used for this (Magurran 2004). For species diversity all plants in quadrats were included. Species richness and introduced and native species richness were used to determine plant community composition by calculating proportions in percentages of the total species richness occupied by the various vegetation growth forms (tree, shrub, forb, graminoid, bryophyte).

Total species richness was obtained by combining species lists from all permanent quadrats and walk through assessments in the plots and then removing duplicates. Native species richness was calculated by subtracting known introduced species from total species richness. Unknowns were included in species richness calculations. Bryophytes were not collected and identified to species in 2012; therefore, the individual number of bryophyte species is not included in total species richness as it resulted in incomparable data sets.

Specimens of *Elymus trachycaulus* (Link) Gould ex Shinners (slender wheat grass), *Elytrigia repens* (L.) Gould (quack grass) and *Elymus hirsutus* J. Presl were difficult to differentiate. They were kept separate in the final data set, as they all occurred. Willow was identified as *Salix* sp., indicating one species of willow, unless more than one distinct species of willow occurred in the quadrat. If there was more than one species, they were numbered (*Salix* sp. 1, *Salix* sp. 2).

Plants that could not be identified to species, were identified to genus, potentially resulting in replicate observations, elevating species richness. For example, if *Melilotus* sp. had no flowers to differentiate *Melilotus officinalis* (L.) Lam. (yellow sweet clover) from *Melilotus alba* Medik. (white sweet clover), it was recorded as *Melilotus* sp. For analysis, if *Melilotus officinalis* and *Melilotus alba* were in a plot, *Melilotus* sp. was removed. This issue was dealt with for a number of genera that could not be identified to species to avoid double counting. *Salix* spp., *Carex* spp. and other plants identified to genus were included in the richness count unless specified above.

Number of quadrats (subsamples) differed in 2011 and 2012 affecting species richness as it is a function of area sampled, with more quadrats resulting in higher richness. Systematic, detailed walk throughs found additional plant species more effectively than additional quadrats would have because of the uneven distribution of infrequently occurring species. Walk throughs eliminated species richness differences between years that could result from different numbers of quadrats in 2011 and 2012. Walk throughs were able to identify species not in the quadrats and because quadrats were subsamples of experimental units, no data adjustment (rarefraction) was needed. Species data from walk throughs were added to quadrat data for analysis.

Woody plant density is the stem count of both tree and shrub growth forms. *Rubus ideaus* L. (wild red raspberry) density was determined by counting a clump of stems emerging from one location as a single plant, since multiple stems can emerge from the same spot. Woody plant density was calculated as total shrubs and trees quadrats divided by the number of quadrats surveyed per experimental unit to account for the different numbers of quadrats assessed in 2011 versus 2012.

Size class assessments used two different sizes of quadrats to assess vegetation and woody debris characteristics. Woody debris density values for the 0.25 m^2 quadrats were converted to 1 m^2 by multiplying by 4. This conversion could not be used for species canopy cover, ground cover and species richness data because these parameters are a function of area sampled and the available area for plant growth. Large and medium quadrats were larger in size than fine and small quadrats, but space for growth could be less available. There would be no plants in areas that had large and medium woody debris pieces, compared to fine and small pieces that cover less area. These results are discussed non statistically to account for the incomparable data due to unequal quadrat size.

3.9 Statistical Analyses

A mixed model analysis of variance (ANOVA) was used to compare vegetation parameters within treatment combinations with three factors of interest (block, soil cover, woody debris) using SAS statistical software (version 9.2, SAS Statistical Institute). Rows were treated as blocks and each plot as an experimental unit. Treatment types (soil cover, woody debris) were fixed factors in the mixed model analysis; block was treated as a random factor.

Shapiro-Wilk test was used to determine if residuals of treatment combinations were normally distributed and Levene's test was used to assess homogeneity of variance. For many vegetation properties, outliers resulted in failure of these tests. Scatter plots were examined to assess the outliers; outliers were not outside the natural range of variability and thus were not removed from the analysis. Results with p-values of 0.03 or greater were considered to have passed the test for normality as ANOVA is fairly robust and can account for these minor abnormalities. For parameters with treatment combinations that failed the test for normality, but passed the test for homogeneity of variance, parametric tests were used for the remaining analyses, to account for a small sample size that may attribute to non normally distributed data.

A three way ANOVA using proc mixed in SAS was the parametric test used when data passed all assumption tests. When data failed assumptions for ANOVA, non parametric data were analyzed using permutational ANOVA performed with PERMANOVA v.1.6 (Anderson 2001, McArdle and Anderson 2001). Procedure entries were selected based on the PERMANOVA user guide (Anderson 2005), which selected block as a random factor with two levels (1, 2), soil cover as fixed with two levels (LFH mineral mix, peat mineral mix) and woody debris type as fixed with three levels (*Populus tremuloides*, *Picea mariana*, control). Analysis was based on Bray–Curtis dissimilarities distance; 9,999 permutations of raw data were used in all tests. Significance was determined at $p < 0.100$ since non parametric tests are conservative with lower power than parametric tests (Dytham 2011).

For data that failed the assumptions for ANOVA and required non parametric tests, parametric three way ANOVAs were completed for comparison. Results of parametric and non parametric tests were similar for most parameters, but for those parameters that differed between parametric and non parametric tests, the biological significance was considered to determine if the effects were negligible. Results that were not biologically significant were compared with means and standard deviations rather than with statistics. Both parametric and non parametric p-values are reported in the results section.

Post hoc tests after significant ANOVAs and PERMANOVAs provided pairwise comparisons among treatments. Significant interactions from parametric tests were examined using interaction plots of the least square means and performing an analysis of simple effects using the slice statement in SAS. The slice statement performs a partitioned analysis of the least square means for an interaction (SAS Institute Inc. 2009). Post hoc comparisons by Tukey's test were used to examine significant interactions of the parametric three way ANOVA. Pairwise a posteriori comparisons with PERMANOVA were done following the non parametric three way ANOVA, for treatments with significant differences. Significance was determined at $p < 0.100$ as non parametric tests are conservative with lower power than parametric tests (Dytham 2011).

Two sample t-tests were used to compare 2009 vegetation data from Brown (2010) with 2012 data. Only parameters with significant effects were compared with 2009 data. Parametric student's t-tests were used when data passed normality tests and non parametric Wilcoxon-Mann-Whitney t-tests when data failed the normality tests. T-tests were considered significant at $p < 0.05$ for parametric tests and $p < 0.100$ for non parametric tests, which are conservative with much lower power than parametric tests (Dytham 2011).

Correlation analysis was used to examine relationships among select vegetation parameters with estimated woody debris volumes and site characterization data (slope, aspect). Only vegetation parameters that had woody debris as a significant factor during ANOVA were compared to woody debris volume and only vegetation parameters that had block as a significant factor during ANOVA were compared to slope and aspect. Parameters that had woody debris or block as factors in a significant interaction were not analyzed. This is because any positive or negative relationship would be difficult to directly correlate to the factor of interest (block or woody debris) if the interacting factors could contribute to the effects. Pearson correlation was used to test the parametric data and Spearman rank correlation was used on the non parametric data that failed the Shapiro-Wilk test for normality. A Bonferroni correction was applied to the correlation values.

4. RESULTS AND DISCUSSION

4.1 Effect Of Woody Debris And Soil Cover Type On Canopy Cover

In 2011, forb ($p = 0.0147$), introduced species ($p < 0.0001$) and bryophyte ($p <0.0001$) cover were significantly greater in peat mineral soil mix than LFH mineral soil mix; graminoid ($p < 0.0001$), shrub ($p < 0.0001$), native species ($p = 0.0018$) and total canopy cover ($p < 0.0001$) were significantly greater in LFH mineral soil mix (Table 3.1). Archibald (2014), Brown (2010) and Mackenzie and Naeth (2007) found similar results associated with LFH mineral soil mix and peat mineral soil mix covers. Block was a significant factor for graminoid ($p = 0.0273$) and native species (0.0012) cover. Tree cover ($p = 0.0458$) was significantly greater in *Picea mariana* than *Populus tremuloides* and control treatments. Shrub cover had a significant block and soil cover type ($p = 0.0139$) interaction, being greater in LFH than peat mineral soil mix.

In 2012 woody debris type, soil cover type and block had no significant effect on either forb or tree cover (Table 3.2). Total canopy cover was significantly greater on LFH mineral soil mix than on peat mineral soil mix ($p = 0.0059$). Block was a significant factor for cover of native species ($p = 0.0151$). Inherent variability of the site or the small sample size ($n = 6$) may have contributed to the significant effect. Block ($p < 0.0001$), soil cover type ($p <0.0001$) and woody debris type ($p = 0.0217$) were all significant factors for graminoid cover, which was significantly greater in LFH mineral soil mix than peat mineral soil mix. Graminoid cover was significantly greater in controls ($p = 0.0254$) than *Picea mariana* woody debris, but not significantly different than *Populus tremuloides*. Block ($p = 0.0054$) and soil cover type ($p < 0.0001$) significantly affected shrub cover. Introduced species cover was significantly greater on peat mineral soil mix than on LFH mineral soil mix ($p < 0.0001$). Soil cover type and woody debris type significantly interacted for introduced species cover ($p = 0.0048$). Bryophyte cover was significantly greater in peat mineral soil mix than LFH mineral soil mix ($p < 0.0001$). There was an interaction between block and soil cover type ($p = 0.0051$), and soil cover type and woody debris type ($p = 0.0033$). Bryophyte cover was significantly higher in controls than in both *Populus tremuloides* ($p = 0.0146$) and *Picea mariana* ($p = 0.0026$) woody debris types.

In both LFH mineral soil mix and peat mineral mix soil mix, shrub cover and introduced species cover differed significantly between 2009 and 2012 (LFH $p < 0.0001$; peat $p < 0.0001$) (Table 3.9). Shrub cover increased, while introduced species cover decreased. There was a significant difference for peat mineral soil mix and LFH mineral soil mix in 2009 relative to 2012 for bryophyte cover (LFH $p = 0.0007$; peat $p < 0.0001$). Bryophyte cover decreased in LFH mineral soil mix between 2009 and 2010, and increased on peat mineral soil mix. Native species cover ($p < 0.0001$) and tree cover ($p < 0.0001$) increased significantly with time in peat mineral soil mix. Tree cover and native species cover did not differ significantly between years for LFH mineral soil mix. Total canopy cover decreased significantly in LFH mineral soil mix from 2009 to 2012 ($p < 0.0001$), with little change in peat mineral soil mix.

Graminoid, shrub, bryophyte and native species cover were not significantly correlated to slope or aspect. The various visual differences with slope position are discussed below in section 4.7 in this chapter.

These differences with soil cover type were likely associated with the seed banks in the materials. Peat mineral soil mix was of lowland origin and hence likely to have more bryophyte propagules. However, most bryophytes were colonizing, early successional species not typically found in lowland areas. A greater cover of bryophytes on peat mineral soil mix is likely due to the ability of bryophytes to withstand harsh environments with fluctuating periods of water and desiccation. The larger number of introduced species in peat mineral soil mix is of interest and may potentially result from the lower canopy cover in general, permitting establishment of aggressive introduced species. Greater tree cover in *Picea mariana* treatments was likely due to an increased number of *Picea mariana* seedlings from the cones that were deposited with the woody debris. Seedlings emerging from cones of applied woody debris emphasize that woody debris, and not just the seed bank of the soil cover, acts as a source of propagules for the plant community. Application of woody debris species that corresponds to the same end land use that the material was sourced from (upland, lowland) is important to facilitate the health and survival of seedlings emerging from woody debris propagules.

4.2 Effect Of Woody Debris And Soil Cover Type On Ground Cover

In 2011 there was no significant effect of woody debris type, soil cover type or block on live vegetation cover (Table 3.3). There was a significant effect of block on bare ground ($p = 0.0188$) Mean bare ground cover in all peat mineral soil mix treatments was greater at 3.6 % ($n = 18$) relative to LFH mineral soil mix at 0.5 %. Litter cover was significantly affected by woody debris type with a significant interaction between block and soil cover type. Litter cover was significantly lower in *Populus tremuloides* ($p = 0.0043$) and *Picea mariana* ($p = 0.0347$) woody debris types than controls. Litter cover was numerically greater on LFH mineral soil mix in block 1 (upper row), with no explanation for this effect. Mean litter cover on all peat mineral soil mix treatments was 69.1 %, considerably lower than on LFH mineral soil mix at 85.0 %. Litter cover on all controls treatments with no woody debris was 83.4 %, which was greater than both *Populus tremuloides* and *Picea mariana* treatments, at 72.6 and 75.3 %, respectively.

In 2012 there was no significant effect of woody debris type or block on live vegetation cover (Table 3.4). There was a significant effect of soil cover type on bare ground ($p = 0.0147$). Bare ground in peat mineral soil mix increased from 2011 and was higher at 4.2 % relative to LFH mineral soil mix at 0.2 % (Table 3.9). Bare ground in LFH mineral soil mix decreased from 2011 to 2012. Litter cover was significantly affected by soil cover type with a significant interaction between block and soil cover type. As in 2011, litter cover was greater in LFH mineral soil mix in block one. Litter cover decreased in both soil cover types from 2011 to 2012. Peat mineral soil mix had 58.4 % litter cover, relative to LFH mineral soil mix at 82.8 %. Greater litter cover on LFH mineral soil mix may be associated with greater graminoid species cover. Graminoids accumulate higher volumes of litter year after year than trees that had greater cover on peat mineral soil mix.

In both soil cover types, there was a significant difference in bare ground and litter cover between years (LFH $p < 0.0001$; peat $p < 0.0001$) (Table 3.9). Bare ground decreased in LFH mineral soil mix from 16.0 to 0.2 % over three years. Bare ground in peat mineral soil mix decreased from 51.0 to 4.2 %. Litter cover in LFH mineral soil mix increased from 7.3 to 82.8 % over three years and increased in peat mineral soil mix from 4.2 to 58.4 %.

The increased litter cover and decreased bare ground cover is common in early plant community succession. Plants grow and reproduce and produce litter. Eventually a decrease in available bare ground limits plant establishment to species that require lower levels of resources and are more tolerant of environmental factors such as shade and limited water and nutrients (Connell and Slatyer 1977). Species with these tolerances are generally mid to late successional species and the transition of bare ground and litter cover from the site conditions identified by Brown (2010) to those of 2011 and 2012 indicate that reclamation is following a successional trajectory to a later seral plant community.

4.3 Effect Of Woody Debris And Soil Cover Type On Plant Species Richness

In 2011 there were no significant effects of woody debris type, soil cover type or block on forb, shrub, native or total species richness (Table 3.5). There was a significant block effect on graminoid species richness ($p = 0.0014$), with graminoid richness higher in block 2 (lower row).

Introduced species richness was significantly higher in peat mineral soil mix than in LFH mineral soil mix ($p < 0.0001$), with block a significant factor ($p = 0.0210$). Tree species richness had a significant block and soil cover type interaction ($p = 0.0404$), being higher in LFH mineral soil mix in block 1 (upper row).

In 2012 there was no significant effect of woody debris type, soil cover type or block on forb, shrub or tree species richness (Table 3.6). There was a significant effect of block on graminoid ($p = 0.0060$), native species ($p = 0.0139$) and total species richness ($p = 0.00396$). Shrub ($p = 0.0291$), introduced ($p = 0.0002$) and total species richness ($p = 0.0446$) were significantly higher in peat mineral soil mix than in LFH mineral soil mix.

Graminoid, native and total species richness were all significantly affected by block and were analyzed for relationships with slope and aspect. Native species richness was significantly correlated to aspect ($p = 0.0409$). Graminoid and total species richness were not significantly correlated to slope or aspect.

On both LFH mineral soil mix and peat mineral mix there was a significant difference in native species and total species richness with years (LFH $p < 0.0001$; peat $p < 0.0001$) (Table 3.9). Native species richness on LFH mineral soil mix increased from 10.3 to 33.3 species over three years. Native species richness on peat mineral mix increased from 5.3 to 35.4 species. Total species richness on LFH mineral soil mix increased from 12.8 to 38.5 species. Total species richness on peat mineral soil mix increased from 8.6 to 42.7 species over three years.

A total of 14 bryophytes were identified to species (Table 3.10). Several specimens could not be identified, which may indicate that total bryophyte species richness is higher than recorded at the time of the field assessment. The highest number of bryophyte species in a single treatment was 12, in peat mineral soil mix *Populus tremuloides*. The lowest number was eight, in peat mineral soil mix *Picea mariana*. Most bryophyte species were early successionals that may have colonized from a variety of sources. However, species such as *Hamatocaulis vernicosus* (Mitt.) Hedenas (brown moss) and *Orthotrichum obtusifolium* Brid. (moss) are associated with cover treatment materials. *Hamatocaulis vernicosus* is a lowland, moderate rich fen species that may have arisen from propagules in the peat seed bank; results of soil chemical analyses suggest the peat mineral soil mix material came from fen peat of a moderate rich fen ecosite. *Orthotrichum obtusifolium* is a species typically found on the trunks of live *Populus tremuloides* trees and was likely brought in with the woody debris material. This species is dependent on the living tissues of trees and nutrients they provide. Over time as the dead trees decay, *Orthotrichum obtusifolium* may die out from lack of live tissues it needs to survive.

4.4 Effect Of Woody Debris And Soil Cover Type On Species Diversity

In 2011 there was no significant effect of woody debris type and soil cover type on species diversity (Table 3.7). Block had a significant, unexplained effect in 2011 ($p = 0.0019$) with significant interactions between block and soil cover type ($p = 0.0362$) and soil cover type and woody debris type ($p = 0.0223$). In 2012 there were no significant effects of woody debris type, soil cover type or block on species diversity (Table 3.8). Species diversity was numerically higher in peat mineral soil mix with any type of woody debris.

Species diversity was similar among years and treatments. Species diversity in peat mineral soil mix in 2011 was 2.3, 2.4 and 2.2 on *Populus tremuloides*, *Picea mariana* and control treatments, respectively, while in 2012 *Populus tremuloides*, *Picea mariana* and control treatment species diversity was 2.6, 2.7 and 2.3, respectively. Species diversity on LFH mineral soil mix in 2011 was 2.1, 2.1, and 2.3 on *Populus tremuloides*, *Picea mariana* and controls, respectively, while in 2012 *Populus tremuloides*, *Picea mariana* and control treatment species diversity was 2.5, 2.6 and 2.5, respectively. The very small increases between years suggest succession is occurring slowly on the study area, despite minimal inputs after initial site construction. No seeding or tree planting was done on the SE dump. Besides woody debris that was placed at the time of construction, only fertilizer was applied to the reclamation area for the first four years. Woody debris has helped stage the successional pathway to create a sustainable ecosystem.

4.5 Effect Of Woody Debris And Soil Cover Type On Woody Plant Density

In 2011 there was no significant effect of woody debris type or soil cover type on woody plant density (Table 3.7). Block had a significant effect in 2011 ($p = 0.0094$), with slightly higher densities in block 1. Mean woody plant density on peat mineral soil mix was lower than that on LFH mineral soil mix. In 2012, there was no significant effect of woody debris type on woody plant density (Table 3.8); however, block ($p = 0.0320$) and soil cover type ($p = 0.0414$) had significant individual effects on woody plant density. Woody plant density in peat mineral soil mix was significantly lower than in LFH mineral soil mix.

Brown (2010) and Naeth and Brown (2014) found significant differences between woody debris treatments and woody plant density in 2008 and 2009. Although not statistically significant, the trend continued in 2011 and 2012 (Tables 3.7, 3.8). *Picea mariana* woody debris had highest woody plant density, likely a result of *Picea mariana* seedling establishment from cones brought in with woody debris. *Picea mariana* is difficult to grow in reclaimed oil sands sites, primarily because few disturbed areas are reclaimed to low lying poor fens or bogs where *Picea mariana* is typically found. It can occur in forested uplands, but these target ecosite phases can be difficult to achieve. Seedlings from cones may have better survival since conditions select the fittest seeds to survive the harsh early succession conditions (Brown 2010). A combination of suitable habitat created by microsites next to woody debris and the southeast exposure of the research area that promotes opening of *Picea mariana* semi-serotenous cones may contribute to the higher density of woody plants with *Picea mariana* woody debris.

There was no significant correlation between woody plant density and slope (2011 $p = 0.2640$; 2012 $p = 0.3560$). There was also no significant correlation between woody plant density and aspect in 2011 and 2012 ($p = 0.1217$; $p = 0.2170$, respectively).

On both LFH mineral soil mix and peat mineral soil mix there was a significant difference in woody plant density between years (LFH $p < 0.0001$; peat $p < 0.0001$) (Table 3.9). Mean woody plant density in both soil cover types increased considerably over three years. Mean woody plant density increased over three years on peat mineral soil mix from 2.1 to 12.6 plants/m^2 and from 2.6 to 16.4 plants/m^2 on LFH mineral soil mix.

4.6 Plant Group and Species Composition Within Treatments

In 2011, forbs formed the highest proportion of plant growth forms in all treatments, followed by graminoids, shrubs and trees (Table 3.5). Forbs comprised approximately 53.3 % of all species, graminoids made up 26.9 %, shrubs 12.4 % and trees 4.8 %. There was a higher proportion of forbs and graminoids on LFH mineral soil mix and a higher proportion of trees and shrubs on peat mineral soil mix. Introduced species made up 15.5 % of the plant community composition and native species 84.5 %. The proportion of introduced species was higher in peat mineral soil mix than LFH mineral soil mix. The trends were the same in 2012 (Table 3.6). Forbs comprised approximately 48.4 % of all species, graminoids 27.8 %, shrubs 16.5 % and trees 5.0 %.

Between 2011 and 2012, the proportion of plant groups with soil cover type did not change except for forbs, which were higher on LFH mineral soil mix in 2011, but almost the same in both soil cover types in 2012 (Tables 3.5, 3.6). The proportion of forbs decreased from 2011 to 2012, while all other plant groups increased.

Vegetation data from 2011 and 2012 were combined to create a list of 119 vascular and non vascular species present on the SE dump (Tables 3.10, 3.11). Twenty one forb, eleven graminoid, five shrub, two tree and seven bryophyte species occurred in all treatments. Seventeen species only occurred in one treatment. Most species present in all treatments were early successionals that frequent naturally and anthropogenically disturbed areas. Six aggressive non native species occurred across the research area including *Bromus inermis* Leyss. (smooth brome), *Chenopodium album* L., *Elytrigia repens, Melilotus* spp. (sweet clover), *Sonchus arvensis* L. (perennial sow thistle) and *Taraxacum officinale* G.H. Weber ex Wiggers (common dandelion). There were considerable species that occur in early to late successional upland forests including *Populus tremuloides, Ribes hudsonianum* Richards. (northern black currant), *Ribes oxyacanthoides* L. (northern gooseberry), *Rosa acicularis* Lindl. (prickly rose), *Lathyrus ochroleucus* Hook. (cream colored vetchling), *Mertensia paniculata* (Ait.) G. Don (tall lungwort), *Petasites frigidus* var. *palmatus* (Ait.) Cronq. (palm leaved coltsfoot) and most graminoids. Mid to late successional species in 2011 and 2012 not recorded by Brown (2010) in 2008 or 2009 included *Pleurozium schreberi* (Brid.) Mitt., (Schreber's moss), *Arctostaphylos uva-ursi* (L.) Spreng. (common bearberry), *Cornus canadensis* L. (bunchberry), *Lonicera villosa* (Michx.) Schult. (mountain honeysuckle), *Oryzopsis pungens* (Torr. ex Spreng.) Dorn (northern rice grass), *Ribes triste* Pallas (wild red currant) and *Viola adunca* Sm. (early blue violet) (Tables 3.10, 3.11). These species tend to grow in a variety of ecosites in early to late successional stages (Beckingham and Archibald 1996). The presence of these species in years four and five following reclamation indicates favourable site conditions for a successional trajectory shaped by species establishing from the soil seed bank.

4.7 Effect Of Slope And Aspect On Vegetation

There was a distinct change in slope between block 1 and 2, moving east to south across the research site (Figure 3.3). The first seven plots in both blocks 1 and 2 on the east end had similar slope gradients from -6 to -8 %. Moving to the south end of the research site, the slope gradients of blocks 1 and 2 diverge in opposite gradients. The remaining 11 plots on the south end in block 1 level out to a minimum of -2 % slope, while in block 2 slope increases to a maximum of -11 %.

There was no distinct trend in aspect either across the research site or between blocks 1 and 2 in the research site (Figure 3.4). The first 6 plots on the east end of the research site have faintly converging aspects moving to the south end of the site. Aspect changed in the first six plots on the east end in block 1 from 119 to 114 degrees, moving east to south, while aspect in block 2 changed from 111 to 115 degrees, with variations to 107 and 108 degree aspects. Aspect in the remaining 12 plots moving to the south end of the research site varied to the extent that no trend was visible.

Only native species richness was significantly correlated with aspect ($p = 0.0409$). Although slope and aspect were not significantly correlated to most vegetation parameters, the distinct difference in slope between rows of the study area and across the span of the site is highly visible and likely affecting the plant community. Visual differences in plant communities between treatments with different slope and aspect included increased litter and graminoid cover with level slope gradients compared to plots with steeper slope gradients. Steeper slopes on the bottom row may have been subject to water erosion of the soil early after construction, which can affect plant community distribution. Woody debris is an effective method for controlling erosion (Harmon et al. 1986, Stevens 1997, Whisenant 2005, Government of Alberta 2009). Nurse crops were not planted on the SE dump as part of reclamation, so until vegetation cover was great enough to protect soil from rain and wind erosion, woody debris was used as the amendment to mitigate erosion. In 2011 and 2012, visual observations of water erosion are not pronounced on the SE dump and erosion was not a parameter considered in this study. This difference in topography may also have an effect on site hydrology and subsurface water movement that contributes to variations in plant community development. Hydrology was not considered in the study due to time limitations and research foci.

The research area lies in a generally southeast facing direction. Southeast facing slopes experience high sun exposure and the more south facing a slope is the more soils and vegetation are prone to desiccation. South facing slopes can receive up to six times higher solar radiation than north facing slopes (Auslander 2003). The most south facing experimental unit had an aspect of 120 degrees and the most east facing experimental unit was 107 degrees. Even though the difference in aspect is not large, minor variations can have profound effects on spatial distribution of vegetation (Åstrôm et al. 2007). Both vascular and non vascular species can be sensitive to microclimatic changes, including temperature. Species of bryophytes in particular that have poor dispersal abilities may rely heavily on moisture availability for dispersal, so south exposure can drastically impact this vegetation group, along with other vegetation parameters. Although slope and aspect are important on a micro scale, small differences in these parameters at this level can have significant implications on a landscape level.

4.8 Effect Of Woody Debris Size Class And Volume On Vegetation

In LFH mineral soil mix woody plant density was greatest in small size class quadrats for both *Populus tremuloides* and *Picea mariana* woody debris types, followed by fine, medium and large size classes (Figure 3.5). Woody plant density was greater on *Picea mariana* woody debris than *Populus tremuloides* for the corresponding size classes. The highest woody plant density on LFH mineral soil mix was 32.0 plants/m^2 on *Picea mariana* small size class quadrats and the lowest was 12.0 plants/m^2 on *Populus tremuloides* large size class quadrats. In peat mineral soil mix woody plant density in size class quadrats were similar for *Populus tremuloides* and *Picea mariana* woody debris types (Figure 3.6). Density was slightly higher in fine and small size class quadrats than in medium and large size class quadrats. This could result from more available area for seedlings to emerge as large and medium pieces are not occupying the space. Lowest density occurred in a *Populous tremuloides* large size class quadrat, with only 9.2 plants/m^2 and highest density occurred in a *Populous tremuloides* fine size class quadrat, with 17.3 plants/m^2.

Graminoid and shrub cover was higher on LFH mineral soil mix than peat mineral soil mix for fine, small, medium and large size class quadrats (Tables 3.15, 3.16). Tree and bryophyte cover were greater on peat mineral soil mix than on LFH mineral soil mix for fine, small, medium and large size class quadrats. Total canopy cover was greatest in large size class quadrats for *Populus tremuloides* and *Picea mariana* with both soil cover types except for peat mineral soil mix *Picea mariana* treatments that had greatest total canopy cover in medium size class quadrats. Forb, graminoid, tree and bryophyte cover was variable across the different size class quadrats on LFH mineral soil mix. Shrub cover was greater in medium and large size class quadrats than fine and small size class quadrats on LFH mineral soil mix. There was no tree cover in any of the size quadrats on LFH mineral soil mix. Forb, graminoid, shrub, tree and bryophyte cover was variable across the different size class quadrats on peat mineral soil mix.

Litter cover was greater in LFH mineral soil mix than peat mineral soil mix and greater in fine and small size class quadrats than medium and large size class quadrats for both soil cover types (Tables 3.17, 3.18). Bare ground cover was greater in peat mineral soil mix than LFH mineral soil mix, but there was no trend associated with bare ground cover and size class quadrats. Live vegetation cover was variable across size class quadrats and soil cover types.

Woody debris volume was directly related to woody debris size class. Woody debris volume in fine size class quadrats was lowest of all quadrats (Table 3.19). As size classes increased, woody debris volume increased, with the exception of large size class quadrats on peat mineral soil mix *Picea mariana* treatments, which had greater volume in medium size class quadrats than large. This may be due to woody debris pieces with large diameters classified as large size classes, but having short length, which would reduce total volume of the woody debris piece.

Woody debris size class is an important characteristic that contributes to woody debris decay, along with woody debris species and substrate quality and microclimatic factors such as temperature, soil contact and soil water (Shorohova and Shorohov 2001, Stokland 2001, Laiho and Prescott 2004). As different size classes of woody debris begins to decompose, the decay rate varies and is faster for smaller size class pieces than large pieces. Variability in decay rates and decay stages of woody debris in a reclamation area can enhance species richness and species composition, particularly for bryophytes that use woody debris as a substrate to promote specific bryophyte assemblages. As woody debris decomposes, it becomes softer and spongier, increasing water holding capacity and buffering the surrounding microclimate (Rambo and Muir 1998). Community composition, distribution, diversity and richness are strongly influenced by heterogeneity, distribution and availability of microhabitats, more of which are created as woody debris decays at various rates (Cole et al. 2008, Økland et al. 2008).

Woody debris decay stage was not a factor considered in the study; however, observations during field assessments suggest woody debris is in early stages of decay with most exhibiting signs of decay class 2. Decay class 2 is characterized by solid wood consistency, sapwood slightly rotting, large twigs present and wood of original color (Yan et al. 2006). As woody debris decays, there is concern for nitrogen immobilization in the soil. Aerial fertilization occurred on the site between 2008 and 2011, and possibly in 2012. Fertilizer does not appear to have had an effect on woody debris decomposition and may actually delay nitrogen immobilization as woody debris decomposes and releases carbon to the soil because of the fertilizer inputs.

4.9 Effect Of Woody Debris Volume Application Rates On Vegetation

Volume of woody debris applied varied with woody debris type. Peat mineral soil mix and LFH mineral soil mix controls had a mean of 0.2 and 1.8 m^3/ha of woody debris, respectively, where no woody debris was applied (Figure 3.7). Woody debris on controls is from residuals mixed with covers. *Populus tremuloides* woody debris had the largest volume of woody debris applied with a mean of 74.0 m^3/ha on peat mineral soil mix and 72.8 m^3/ha on LFH mineral soil mix, while *Picea mariana* woody debris type had a mean of 59.0 m^3/ha on peat mineral soil mix and 44.6 m^3/ha on LFH mineral soil mix applied. Woody debris application rates ranged from 32.0 m^3/ha on a *Picea mariana* plot to 117.9 m^3/ha on a *Populus tremuloides* plot. Although *Populus tremuloides* woody debris type had higher volumes, they had fewer pieces per plot. Volume is greater in *Populus tremuloides* woody debris type because pieces were in the large size class, while *Picea mariana* woody debris type had more pieces, in medium and small size classes.

There was a significant difference between woody debris type and block ($p = 0.0019$; $p = 0.0540$, respectively) and a significant interaction between block and woody debris type ($p = 0.0226$), indicating *Populus tremuloides* volumes were greater in block 2 than in block 1. Greater volumes in block 2 are likely due to uneven application of woody debris across the site by the operator during construction and are not a result of erosion to down slope positions. Woody debris type had a significant effect on woody debris volume ($p = <0.0001$). There is also a significant difference between pairwise comparisons. Woody debris volume of *Populus tremuloides* was significantly different than that of *Picea mariana* ($p = 0.0302$) and *Populus tremuloides* volumes were significantly different than controls ($p = <0.0001$). *Picea mariana* volume application rates were significantly different than controls ($p = <0.0001$).

Only moss and graminoid cover were compared to woody debris volume because both were the only vegetation parameters that had woody debris type as a significant factor following ANOVA. It was hypothesized that if woody debris type did not affect vegetation parameters, then the volume of woody debris would not affect these parameters either. Neither graminoid cover ($p = 0.5637$) nor moss cover ($p = 0.2835$) were significantly correlated to woody debris volume.

Correlation analysis did not suggest a negative or positive relationship of woody debris volume with vegetation. Thus ranges of woody debris volume applied to the plots function equally to facilitate plant community development. As little as 32.0 m^3/ha and as high as 117.9 m^3/ha was applied on the research area, supporting that even lower application rates than those suggested by Vinge and Pyper (2013) can have positive effects for reclamation. Vinge and Pyper (2013) recommend application rates of 60 to 100 m^3/ha on upland reclaimed sites; however, these rates may be too high or not necessary. Application rates of 50 to 75 m^3/ha, which is similar to what was applied on the *Populus tremuloides* and *Picea mariana* woody debris types, provide positive ecological effects for plant community development, erosion control, microsite establishment and facilitates trajectories for sustainable successional pathways in reclamation.

Although volume is measurable for reclamation application, it should not be the only factor to consider when evaluating amendment materials. Distribution and placement of woody debris affects ground cover and bare ground for vegetation to emerge from. Dense placement can inhibit plant emergence and function similar to mulched woody material that can immobilize nutrients and insulates soil to create frozen layers (Corns and Maynard 1998, MacIsaac et al. 2003, Landhäusser et al. 2007, Government of Alberta 2009). Variability of size classes is important for long term succession. Woody debris diameter is one of several factors that affects decay rate (Shorohova and Shorohov 2001). Diameters less than 10 cm decompose faster than diameters greater than 10 cm (Stokland 2001). Different size classes will decay at different rates throughout succession, which is important to increase site variability that promotes higher plant species richness and species diversity. Volume may not be as important to evaluate application of woody debris material as distribution of size classes and placement of the material.

4.10 Woody Debris Cover Application Rates

Woody debris cover application rate per plot was calculated from the 2012 mean cover values in the 15 permanent quadrats. Covers of all size classes in each quadrat were summed and a mean value per plot provided the final cover application rate in year five following site construction. *Picea mariana* woody debris cover was greater than *Populus tremuloides* cover. *Picea mariana* covers were 16.0 and 12.9 % on peat mineral soil mix and LFH mineral soil mix, respectively and *Populus tremuloides* covers were 13.8 and 10.3 % on peat mineral soil mix and LFH mineral soil mix, respectively (Figure 3.8).

In 2011 there was no significant effect of block on total woody debris cover; however, there was a significant interaction between soil cover type and woody debris type ($p = 0.0299$) (Table 3.13). Woody debris type ($p < 0.0001$) and soil cover type ($p = 0.0044$) were significant factors individually. There is more woody debris on peat mineral soil mix than LFH mineral soil mix and both *Populus tremuloides* and *Picea mariana* had greater total woody debris cover than controls. Mean total woody debris cover for LFH mineral soil mix with *Populus tremuloides*, *Picea mariana* and control was 11.0, 10.8 and 0.9 %, respectively. Mean total woody debris cover for peat mineral soil mix with *Populus tremuloides*, *Picea mariana* and control was 14.9, 16.3 and 0.2 %, respectively. All values were higher in peat mineral soil mix except for controls.

In 2012 there was no significant effect of soil cover type or block on total woody debris cover (Table 3.14). Total woody debris cover was significantly different between the woody debris types ($p = 0.0013$). Mean total woody debris cover for both soil cover types combined was significantly lower on *Populus tremuloides* at 12.0 % than *Picea mariana* at 14.4 % ($p = 0.0329$). Total woody debris cover for *Populus tremuloides* ($p < 0.0001$) and *Picea mariana* ($p < 0.0001$) was significantly higher than controls, which was only 0.3 %.

Total woody debris cover in 2012 was compared to that from 2009 data from Brown (2010). There was no significant difference between years for total woody debris cover on LFH mineral soil mix. Total woody debris cover on LFH mineral soil mix was 9.4 % in 2009 and 10.0 % in 2012 (Table 3.9). Total woody debris cover was significantly higher on peat mineral soil mix in 2009 than in 2012 ($p = 0.06$). Total woody debris cover on peat mineral soil mix decreased from 11.1 % in 2009 to 7.8 % in 2012.

Woody debris cover by size class changed between initial site construction in 2008 and field assessments in 2012 (Tables 3.12, 3.13, 3.14). Woody debris cover on LFH mineral soil mix *Picea mariana* treatments was higher in 2008 than any other year at 22.4 %. It dropped to 10.8 % in 2011 then increased slightly in 2012 to 12.9 %. A large portion of total woody debris cover in 2008 on *Picea mariana* woody debris type that was not found in 2011 or 2012 was fine woody debris. In 2008 12.2 % was fine woody debris, with 0.5 % in 2012. The decrease in cover since plot establishment may be due to wind and water erosion and incorporation of fine woody debris into soil or under litter layers. The slight increase in woody debris cover could be a result of fragmenting of woody debris as it begins to weather and decompose. Brown (2010) found that shortly after plot establishment, mean woody debris cover per plot was 10 to 40 % with *Picea mariana* treatments had higher cover due to greater abundance of small and fine sized woody debris. Total woody debris cover of *Picea mariana* treatments on peat mineral soil mix decreased from 2008 to 2009. Cover was 18.7 % in 2009, 16.3 % in 2011 and 16.0 % in 2012 (Tables 3.12, 3.14). This could be a result of wind and water erosion and incorporation of fine woody debris into soil as fine woody debris cover was 5.3 % in 2008 and 1.7 and 1.3 % in 2011 and 2012, respectively.

Vinge and Pyper (2013) recommend application rates of 10 to 25 % coverage on upland reclaimed sites. In 2011 and 2012 woody debris coverage was between 10 and 16 % and continued to provide positive effects on the plant community and soil. However, the lower rate of coverage in years four and five may not reflect demands for reclamation succession because the plant community has, at this point, grown in and filled part of the role woody debris initially had in stimulating plant growth. Higher application rates for coverage may still be needed early on in reclamation to promote microsite influences and soil protection from erosion (Brown 2010). However, too high coverage rates can have negative effects similar to those associated with mulching and should be avoided or reserved for site specific conditions that require high coverage application rates, such as very steep slopes.

5. CONCLUSIONS

Soil cover type affected plant community properties more so than woody debris. Only tree, total woody debris, graminoid and introduced species covers and woody debris volume had woody debris as a significant factor contributing to differences among treatments. Changes in parameters varied depending on the soil cover type. Block was a significant factor for many vegetation parameters. Slope and aspect did not significantly correlate with any vegetation parameters except for native species richness.

Most vegetation parameters either increased or decreased significantly over three years. Some parameters increased or decreased in both soil cover types between years. Others increased in one soil cover type and decreased in another, or increased or decreased in one soil cover type and stayed the same in the other.

A total of 119 vascular and non vascular plant species were found on the research site, which is likely an underestimation due to a number of bryophytes and vascular plants, including *Salix* spp. and *Carex* spp. not being able to be identified to species. Most species are early successionals that occur in naturally and anthropogenically disturbed areas; there are several species found in 2011 and 2012 that were not found in 2008 and 2009 that can be considered to be mid to late successional.

Woody debris volume and cover did not likely have negative effects on plant community development. Current recommended volume application rates may be high since approximate application rates of 50 to 75 m^3/ha provided positive ecological effects for reclamation. Volume may not likely be as important as distribution of size classes and placement of the material.

Although the lower coverage on the SE dump continues to exhibit positive effects on the plant community, higher coverage rates may be needed early on in reclamation to promote microsite influences and soil protection from erosion. These results show a continual positive relationship between woody debris and soil cover and soil and vegetation development in year five post reclamation, demonstrating the promotion of ecological succession on this disturbed landscape.

Figure 3.1. Oil sands deposits and surface mineable area in north eastern Alberta, Canada (Government of Alberta 2013).

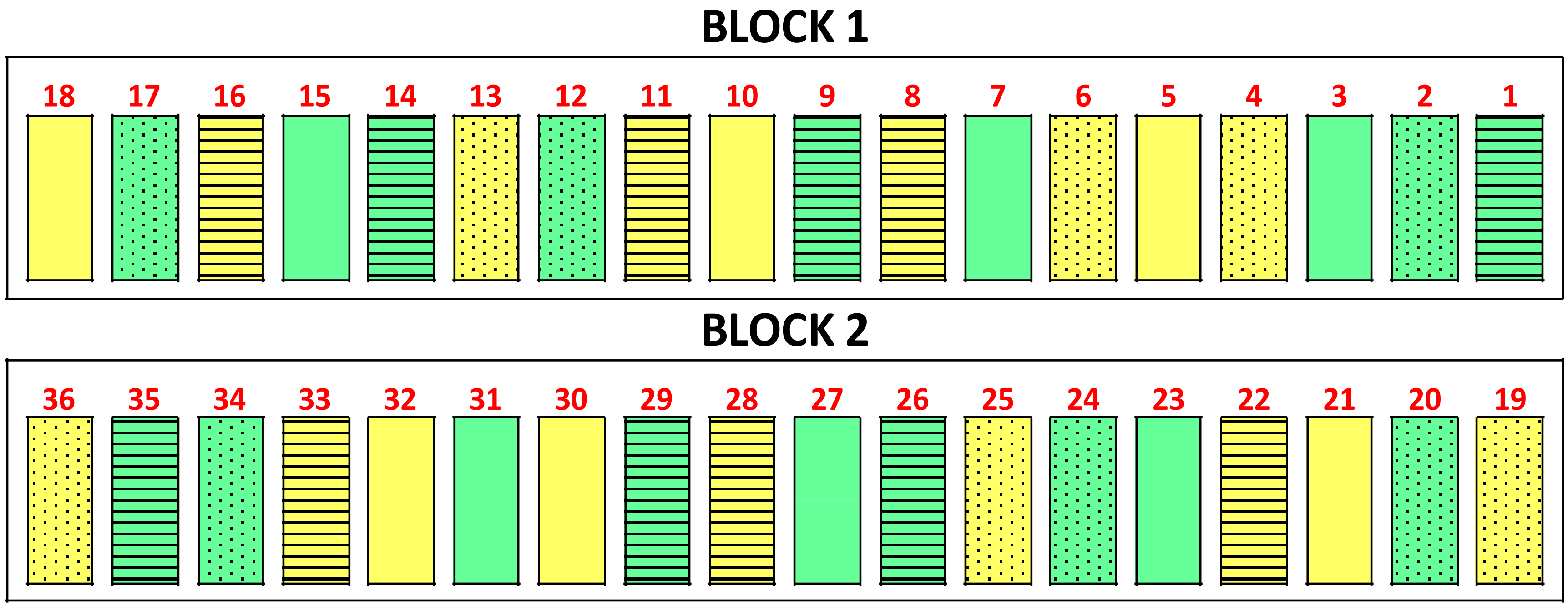

Figure 3.2. Plots on the southeast dump at Suncor Energy Inc. Yellow plots have LFH mineral soil mix cover and green plots have peat mineral soil mix cover. Plots without lines or dots are control plots, plots with dots have *Populus tremuloides* mixed wood woody debris and plots with horizontal lines have *Picea mariana* woody debris (Brown 2010).

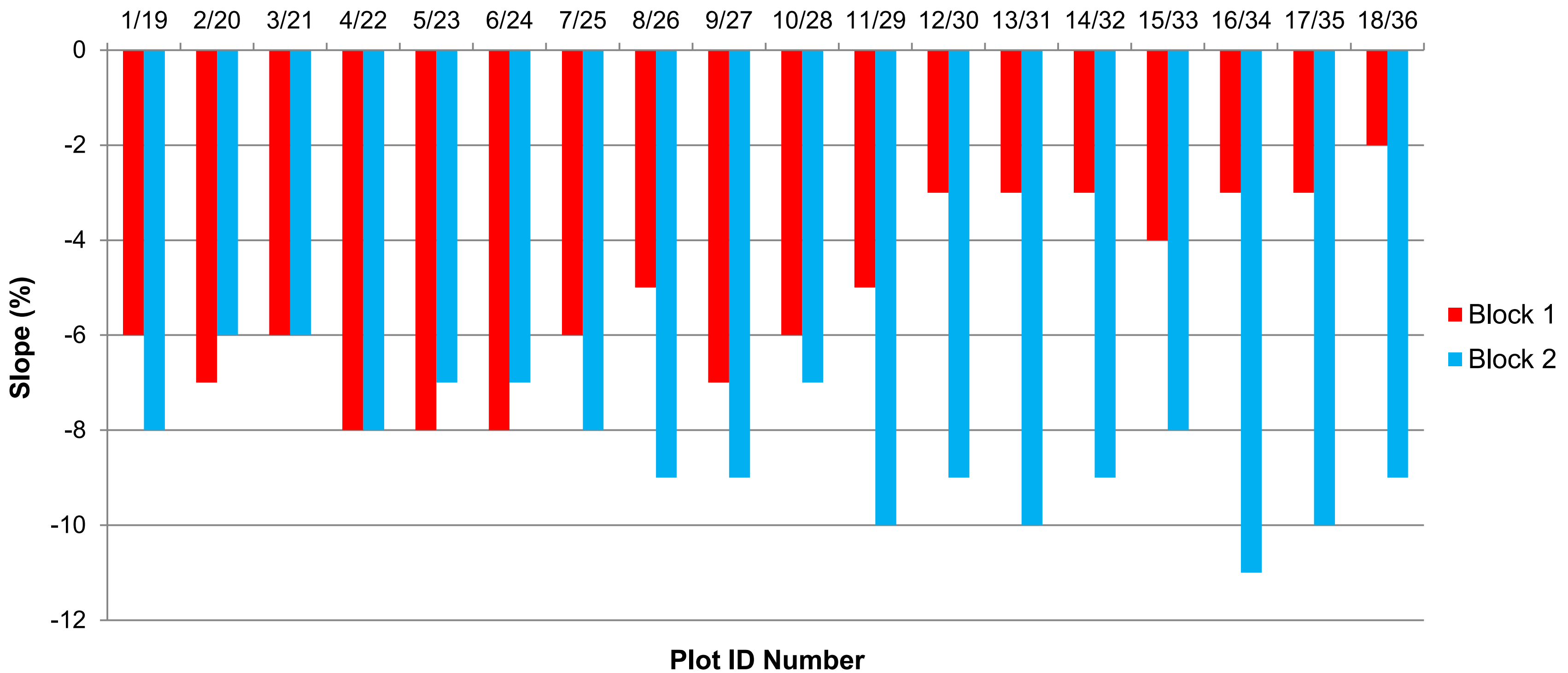

Figure 3.3. Slope of the southeast dump plots moving east to south. Block 1 is the top row of the study area and block 2 is the bottom row. Graph bars are paired by corresponding plots of the top and bottom rows to show the change in slope across the study area.

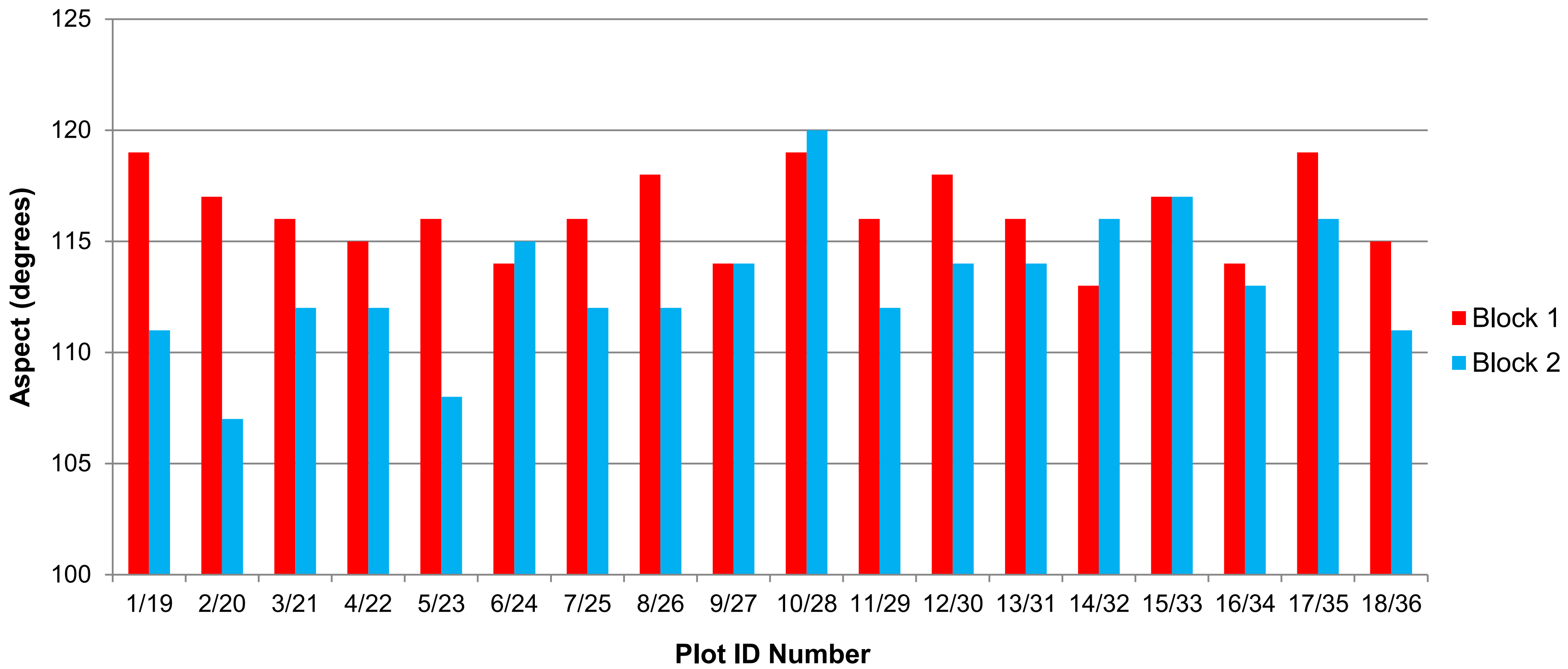

Figure 3.4. Aspect of the southeast dump plots moving east to south. Block 1 is the top row of the study area and block 2 is the bottom row. Graph bars are paired by corresponding plots of the top and bottom rows to show the change in aspect across the study area.

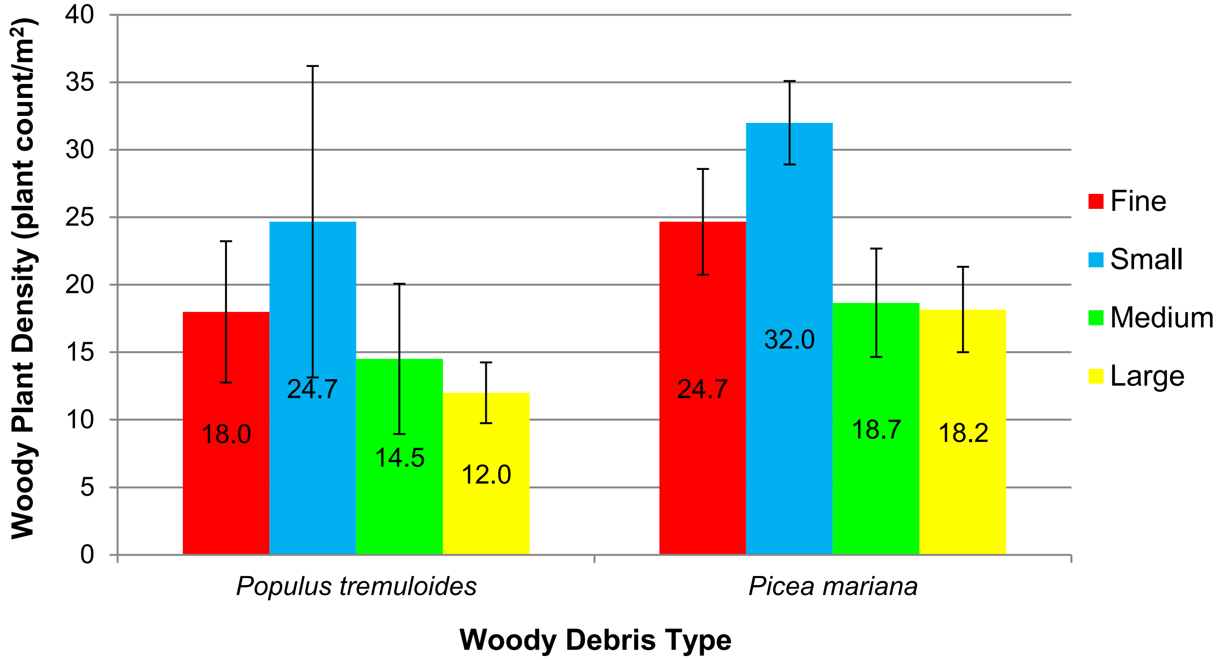

Figure 3.5. Mean woody plant density on LFH mineral soil mix for size class assessments. Numbers within the bars denote mean values. Error bars are standard error of the means, n = 6. Significance was not determined between size class quadrats.

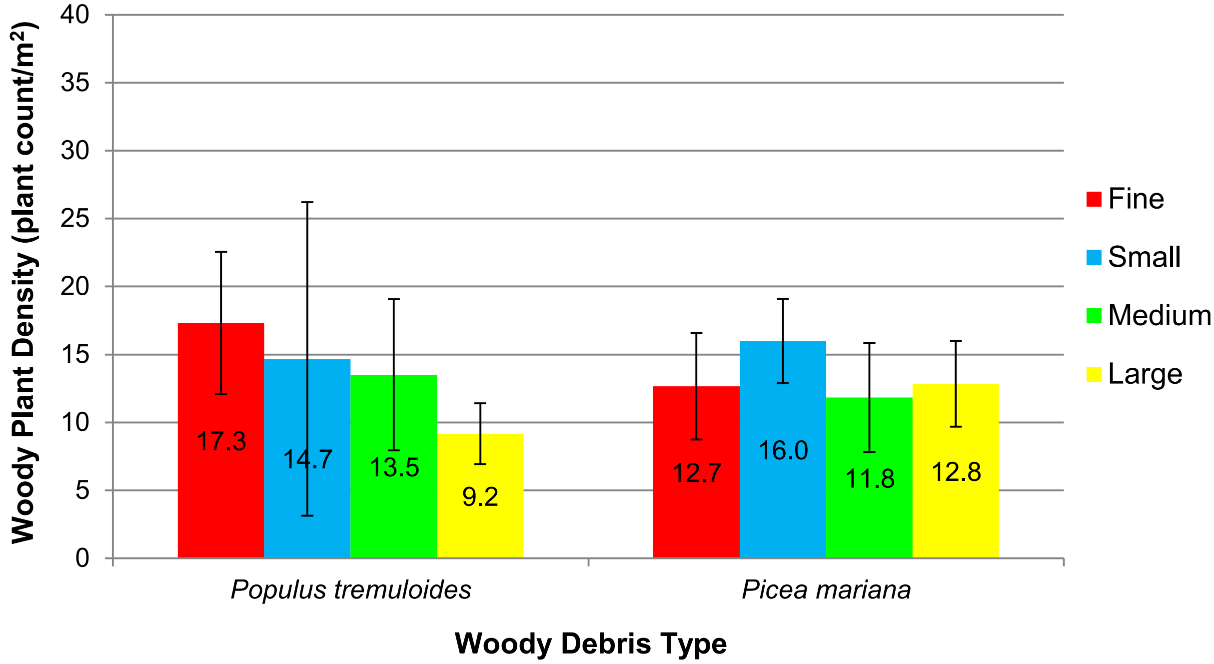

Figure 3.6. Mean woody plant density on peat mineral soil mix for size class assessments. Numbers within the bars denote mean values. Error bars are standard error of the means, n = 6. Significance was not determined between size class quadrats.

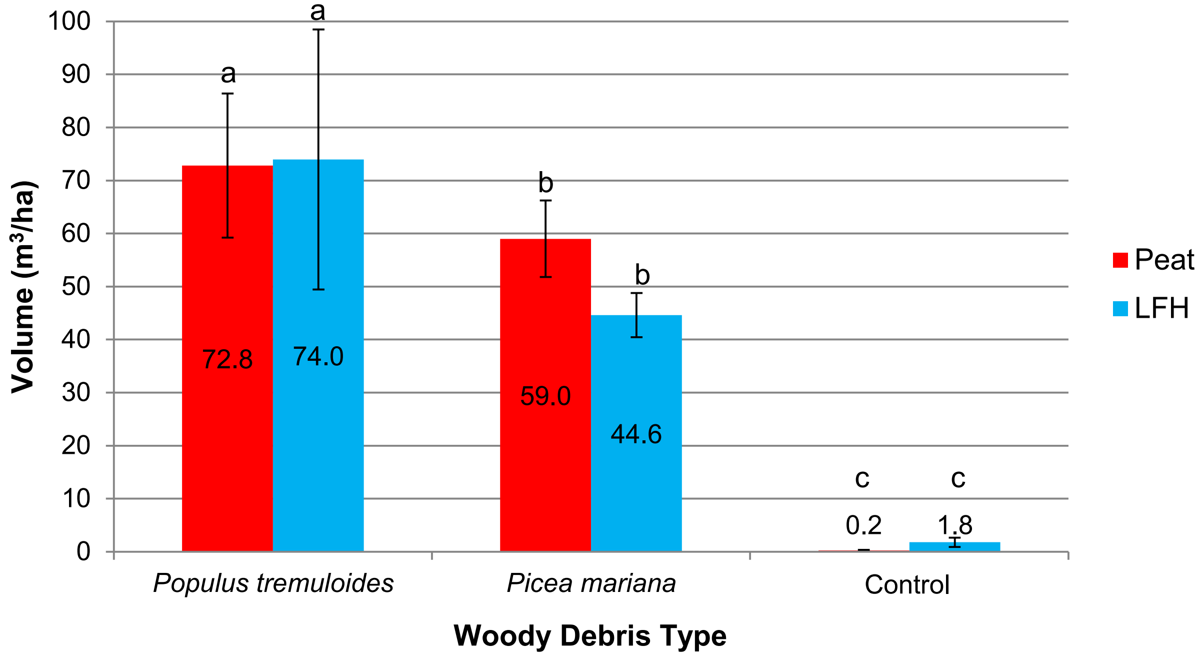

Figure 3.7. Mean woody debris volume application rates in 2012. Numbers within the bars denote mean values. Error bars are standard error of the means, $n = 6$. Letters indicate significant differences between woody debris types within soil cover at $p < 0.100$.

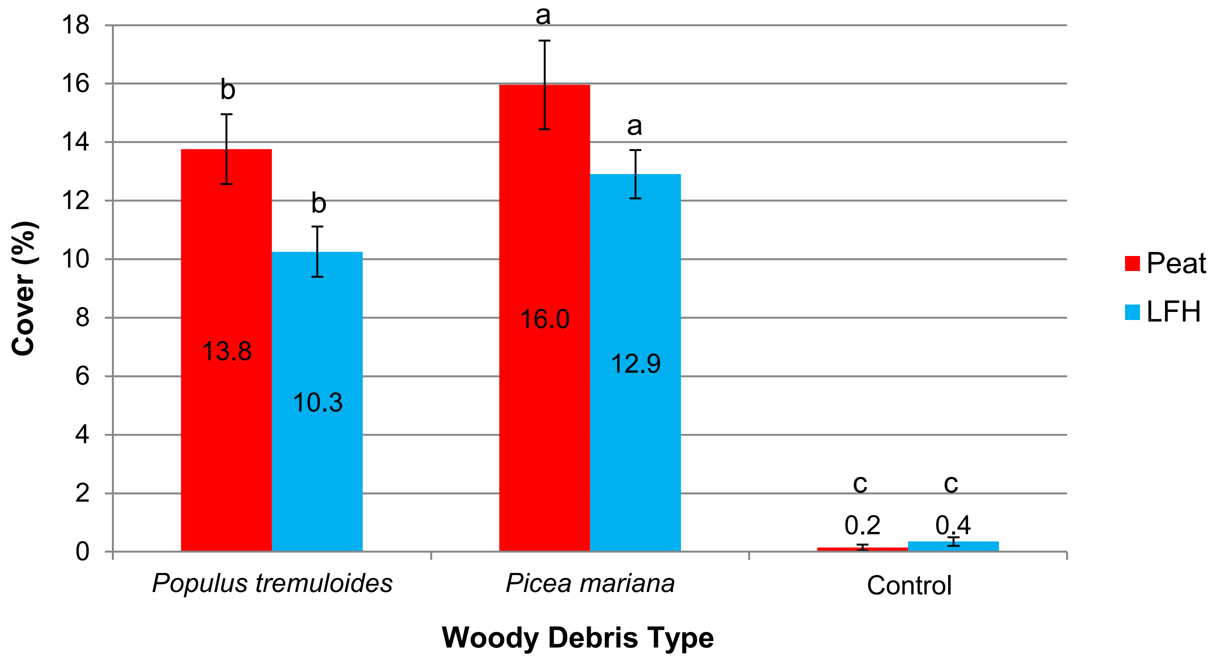

Figure 3.8. Mean woody debris cover application rates in 2012. Numbers within the bars denote mean values. Error bars are standard error of the means, n = 6. Letters indicate significant differences between woody debris types within soil cover at $p < 0.100$.

Table 3.1. Mean percent canopy cover of vegetation growth forms in 2011 by soil cover and woody debris types.

	LFH Mineral Soil Mix			Peat Mineral Soil Mix		
Parameter	*Populus tremuloides*	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Forb	24.3 (2.7)^{b}	21.5 (3.3)^{b}	22.9 (1.6)^{b}	34.3 (5.4)^{a}	29.9 (3.8)^{a}	26.5 (1.4)^{a}
Graminoid	10.8 (2.3)^{a}	11.1 (1.3)^{a}	13.7 (1.4)^{a}	4.4 (0.5)^{b}	3.6 (0.7)^{b}	4.7 (0.8)^{b}
Shrub	26.9 (8.0)^{a}	33.7 (8.0)^{a}	26.4 (9.1)^{a}	10.5 (2.7)^{b}	12.3 (1.6)^{b}	6.4 (2.3)^{b}
Tree	0.1 (0.1)^{B}	0.6 (0.5)^{A}	0.4 (0.4)^{B}	0.4 (0.1)^{B}	1.9 (0.6)^{A}	0.4 (0.4)^{B}
Bryophyte	0.8 (0.4)^{b}	0.2 (0.1)^{b}	1.0 (0.5)^{b}	9.7 (3.5)^{a}	7.2 (1.9)^{a}	12.0 (3.1)^{a}
Native	27.1 (3.7)^{a}	28.7 (2.9)^{a}	25.3 (2.4)^{a}	22.7 (1.9)^{b}	21.0 (1.7)^{b}	20.8 (4.0)^{b}
Introduced	2.8 (0.3)^{b}	2.5 (0.2)^{b}	2.6 (0.4)^{b}	4.9 (0.7)^{a}	4.4 (0.7)^{a}	5.0 (0.5)^{a}
Total	61.5 (4.2)^{a}	59.0 (4.9)^{a}	56.5 (5.0)^{a}	42.9 (3.4)^{b}	42.0 (3.3)^{b}	35.3 (3.4)^{b}

Numbers are means followed by standard errors in brackets, $n = 6$.
Upper case letters indicate significant differences between woody debris type and lower case letters indicate significant differences between soil cover types at $p < 0.05$.

Table 3.2. Mean percent canopy cover of plant growth forms in 2012 by soil cover and woody debris types.

Parameter	LFH Mineral Soil Mix			Peat Mineral Soil Mix		
	Populus tremuloides	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Forb	17.1 (1.9)	16.0 (2.3)	21.1 (2.9)	21.9 (3.2)	21.7 (1.5)	22.0 (1.7)
Graminoid	7.3 (1.0)^{a}	6.2 (0.6)$^{B/a}$	7.9 (0.8)$^{A/a}$	3.5 (0.9)^{b}	2.0 (0.3)$^{B/b}$	3.4 (0.6)$^{A/b}$
Shrub	24.0 (5.2)^{a}	28.6 (4.4)^{a}	21.1 (4.2)^{a}	10.2 (2.6)^{b}	10.8 (1.3)^{b}	6.8 (2.3)^{b}
Tree	0.1 (0.0)	0.4 (0.4)	0.4 (0.2)	0.8 (0.2)	1.8 (0.4)	0.7 (0.4)
Bryophyte	0.3 (0.1)$^{B/b}$	0.3 (0.1)$^{B/b}$	0.6 (0.2)$^{A/b}$	14.0 (3.1)$^{B/a}$	10.6 (3.1)$^{B/a}$	28.2 (5.4)$^{A/a}$
Native	44.6 (3.3)	47.4 (2.0)	49.8 (1.8)	45.1 (5.2)	41.1 (4.4)	54.8 (6.9)
Introduced	4.1 (0.6)^{b}	4.1 (0.5)^{b}	1.3 (0.2)^{b}	5.2 (0.6)^{a}	5.8 (0.7)^{a}	6.6 (0.8)^{a}
Total	43.4 (2.7)^{a}	45.5 (2.1)^{a}	45.2 (1.6)^{a}	33.3 (3.0)^{b}	32.7 (2.2)^{b}	30.5 (3.4)^{b}

Numbers are means followed by standard errors in brackets, $n = 6$.
Upper case letters indicate significant differences between woody debris type and lower case letters indicate significant differences between soil cover types at $p < 0.05$ for parametric tests and $p < 0.100$ for non parametric tests.

Table 3.3. Mean percent ground cover in 2011 by soil cover and woody debris types.

	LFH Mineral Soil Mix			Peat Mineral Soil Mix		
Parameter	*Populus tremuloides*	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Vegetation	6.4 (1.1)	5.8 (0.4)	6.2 (0.5)	7.9 (1.4)	5.7 (0.5)	6.6 (1.3)
Bare	0.6 (0.2)	0.3 (0.1)	0.6 (0.3)	2.5 (0.7)	2.8 (1.3)	5.6 (2.1)
Litter	81.0 (2.1)$^{B/a}$	82.8 (1.7)$^{B/a}$	91.4 (1.2)$^{A/a}$	64.1 (2.7)$^{B/b}$	67.8 (3.5)$^{B/b}$	75.4 (5.1)$^{A/b}$

Numbers are means followed by standard errors in brackets, n = 6.
Upper case letters indicate significant differences between woody debris type and lower case letters indicate significant differences between soil cover types at $p < 0.05$.

Table 3.4. Mean percent ground cover in 2012 by soil cover and woody debris types.

	LFH Mineral Soil Mix			Peat Mineral Soil Mix		
Parameter	*Populus tremuloides*	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Vegetation	8.8 (0.9)	8.0 (0.4)	9.9 (0.7)	8.7 (0.7)	9.0 (1.1)	9.2 (0.7)
Bare	0.1 (0.0)^{b}	0.2 (0.1)^{b}	0.3 (0.1)^{b}	2.4 (0.8)^{a}	6.1 (2.3)^{a}	4.1 (0.7)^{a}
Litter	80.6 (1.6)^{a}	78.8 (1.2)^{a}	88.8 (0.8)^{a}	59.9 (4.5)^{a}	57.4 (1.9)^{a}	57.7 (5.2)^{a}

Numbers are means followed by standard errors in brackets, n = 6.
Different letters denote significance between soil cover types at $p < 0.05$ for parametric tests and $p < 0.100$ for non parametric tests.

Table 3.5. Species richness and species composition of vegetation growth forms in 2011 by soil cover and woody debris types.

Parameter	LFH Mineral Soil Mix			Peat Mineral Soil Mix		
	Populus tremuloides	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Forb	18.0 (0.7)	19.7 (1.6)	19.5 (1.2)	21.0 (0.8)	18.3 (1.4)	16.5 (1.5)
Graminoid	9.7 (0.7)	10.3 (0.6)	9.7 (0.4)	9.8 (1.0)	8.3 (0.8)	9.3 (0.8)
Shrub	4.0 (0.4)	4.3 (0.4)	4.0 (0.4)	4.5 (0.8)	5.3 (0.5)	4.2 (0.5)
Tree	1.3 (0.2)^{A}	1.8 (0.3)^{B}	1.2 (0.2)	1.5 (0.2)^{A}	2.5 (0.2)^{B}	1.8 (0.3)
Bryophyte	0.7 (0.2)	0.7 (0.2)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
Native	29.3 (1.1)	29.3 (1.1)	30.2 (1.0)	31.5 (2.5)	29.7 (1.5)	27.8 (2.3)
Introduced	4.3 (0.3)^{b}	4.3 (0.8)^{b}	5.2 (0.3)^{b}	6.5 (0.8)^{a}	5.8 (0.6)^{a}	5.0 (0.4)^{a}
Total	33.7 (1.4)^{b}	33.7 (1.8)^{b}	35.3 (1.2)^{b}	38.0 (2.2)^{a}	35.5 (1.6)^{a}	32.8 (2.7)^{a}

Numbers are means followed by standard errors in brackets, n = 6.
Upper case letters indicate significant differences between woody debris type and lower case letters indicate significant differences between soil cover types at $p < 0.05$ for parametric tests and $p < 0.100$ for non parametric tests.
All bryophytes were lumped into a single sample category during the field assessment because they could not be identified to the species level in the field; therefore, no significance was determined. Refer to Table 3.10 for complete list of bryophytes

Table 3.6. Species richness and species composition of vegetation growth forms in 2012 by soil cover and woody debris types.

Parameter	LFH Mineral Soil Mix			Peat Mineral Soil Mix		
	Populus tremuloides	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Forb	17.8 (0.6)	19.0 (1.4)	19.3 (1.6)	20.7 (1.3)	21.2 (1.0)	19.8 (1.0)
Graminoid	10.5 (0.8)	12.3 (0.7)	11.8 (0.7)	11.3 (1.0)	9.7 (0.8)	11.8 (0.4)
Shrub	5.0 (0.6)[b]	6.2 (1.1)[b]	5.8 (1.0)[b]	6.7 (1.8)[a]	8.8 (0.8)[a]	7.7 (0.8)[a]
Tree	1.5 (0.2)	2.0 (0.4)	1.3 (0.3)	2.3 (0.2)	2.8 (0.2)	2.2 (0.3)
Bryophyte	1.0 (0.0)	0.8 (0.2)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
Native	31.3 (1.7)	34.5 (2.4)	34.0 (2.9)	34.2 (3.5)	36.0 (2.2)	36.2 (2.1)
Introduced	4.5 (0.2)[b]	5.8 (0.6)[b]	5.3 (0.5)[b]	7.8 (0.8)[a]	7.5 (0.5)[a]	6.3 (0.5)[a]
Total	35.8 (1.8)[b]	40.3 (2.6)[b]	39.3 (3.0)[b]	42.0 (3.2)[a]	43.5 (2.1)[a]	42.5 (2.0)[a]

Numbers are means followed by standard errors in brackets, n = 6.
Upper case letters indicate significant differences between woody debris type and lower case letters indicate significant differences between soil cover types at $p < 0.05$ for parametric tests and $p < 0.100$ for non parametric tests.
All bryophytes were lumped into a single sample category during the field assessment because they could not be identified to the species level in the field; therefore, no significance was determined. Refer to Table 3.10 for complete list of bryophytes.

Table 3.7. Species diversity and woody plant density in 2011 by soil cover and woody debris types.

Parameter	Unit	LFH Mineral Soil Mix			Peat Mineral Soil Mix		
		Populus tremuloides	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Species diversity		2.1 (0.2)	2.1 (0.1)	2.3 (0.2)	2.3 (0.1)	2.4 (0.1)	2.2 (0.0)
Woody plant density	Plant count/m^2	11.0 (2.2)	15.2 (1.6)	12.9 (1.5)	9.6 (2.7)	10.5 (1.4)	9.2 (2.9)

Numbers are means followed by standard errors in brackets, n = 6.
Different letters denote significance between soil cover types at $p < 0.05$.

Table 3.8. Species diversity and woody plant density in 2012 by soil cover and woody debris types.

Parameter	Unit	LFH Mineral Soil Mix			Peat Mineral Soil Mix		
		Populus tremuloides	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Species diversity		2.5 (0.2)	2.6 (0.2)	2.5 (0.2)	2.6 (0.1)	2.7 (0.1)	2.3 (0.2)
Woody plant density	Plant count/m^2	15.1 (2.1)[a]	18.7 (1.4)[a]	15.4 (1.1)[a]	12.7 (3.1)[b]	13.7 (1.7)[b]	11.5 (3.4)[b]

Numbers are means followed by standard errors in brackets, n = 6.
Different letters denote significance between soil cover types at $p < 0.05$.

Table 3.9. Mean vegetation parameters in 2009 and 2012 by soil cover type.

		August 2009		August 2012	
Parameter	Unit	LFH Mineral Soil Mix	Peat Mineral Soil Mix	LFH Mineral Soil Mix	Peat Mineral Soil Mix
Shrub cover	%	3.8 (0.6)[A/b]	1.6 (0.3)[B/b]	24.5 (2.6)[A/a]	9.3 (1.2)[B/a]
Tree cover	%	0.1 (0.0)	0.1 (0.0)[b]	0.3 (0.1)	1.1 (0.2)[a]
Bryophyte cover	%	16.5 (2.6)[A/a]	5.7 (1.0)[B/b]	0.4 (0.1)[B/b]	17.6 (2.9)[A/a]
Native species cover	%	43.4 (2.4)[A]	15.3 (1.7)[B/b]	47.3 (1.4)	47.0 (3.4)[a]
Introduced species cover	%	10.4 (0.8)[B/a]	15.2 (1.4)[A/a]	3.2 (0.4)[Bb]	5.9 (0.4)[A/b]
Total canopy cover	%	60.6 (1.6)[A/a]	31.8 (1.6)[B]	44.7 (1.2)[A/b]	32.2 (1.6)[B]
Bare cover	%	16.0 (1.7)[B/a]	51.0 (2.6)[A/a]	0.2 (0.0)[B/b]	4.2 (0.9)[A/b]
Litter cover	%	7.3 (0.5)[b]	4.2 (0.5)[b]	82.8 (1.3)[A/a]	58.4 (2.3)[B/a]
Total woody debris cover	%	9.4 (1.7)	11.1 (2.0)[a]	10.0 (1.8)	7.8 (1.4)[b]
Native species richness	Count	10.3 (0.7)[A/b]	5.3 (0.4)[B/b]	33.3 (1.3)[a]	35.4 (1.5)[a]
Total species richness	Count	12.8 (0.7)[A/b]	8.6 (0.4)[B/b]	38.5 (1.4)[B/a]	42.7 (1.4)[A/a]
Woody plant density	Plant count/m^2	2.6 (0.3)[b]	2.1 (0.4)[b]	16.4 (0.9)[A/a]	12.6 (1.5)[B/a]

Numbers are means followed by standard errors in brackets, n = 18.
Upper case letters indicate significant differences between soil covers of the same year and lower case letters indicate significant differences between years of the corresponding soil cover at $p < 0.05$ for parametric tests and $p < 0.100$ for non parametric tests.
Species diversity, forb and graminoid cover, ground live vegetation and forb, graminoid, shrub, tree and introduced species richness were not analyzed for comparison amongst years because there was either no significant effect of soil cover, woody debris or block on these parameters in 2012 or the 2009 vegetation data was not available.
2009 data adapted from Brown 2010.

Table 3.10. Presence (+) absence (-) of bryophyte species in 2011 by soil cover and woody debris types.

	LFH Mineral Soil Mix			Peat		
Species	*Populus tremuloides*	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Barbula convoluta Hedw.	+	-	+	+	+	+
Brachythecium oedipodium (Mitt.) Jaeg.	+	-	-	-	-	-
Bryum argenteum Hedw.	+	+	+	+	+	+
Bryum lisae De Not.	+	+	+	+	+	+
Campylium hispidulum (Brid.) Mitt.	-	+	+	-	-	+
Ceratodon purpureus (Hedw.) Brid.	+	+	+	+	+	+
Funaria hygrometrica Hedw.	+	+	+	+	+	+
Hamatocaulis vernicosus (Mitt.) Hedenas	-	-	-	+	-	-
Leptobryum pyriforme (Hedw.) Wils.	+	+	+	+	+	+
Bryophyte spp.	+	+	+	+	+	+
Orthotrichum obtusifolium Brid.	-	-	-	+	-	-
Pleurozium schreberi (Brid.) Mitt.	-	-	-	+	-	-
Pohlia nutans (Hedw.) Lindb.	+	+	+	+	+	+
Polytrichum juniperinum Hedw.	+	+	+	-	-	-
Pylaisiella polyantha (Hedw.) Grout	-	-	-	+	-	-
Total	10	10	10	12	8	9

Scientific names and authorities as per ACIMS (2013) and the USDA plant database (2013).

Table 3.11. Presence (+) absence (-) of plant species, excluding bryophytes, in 2011 and 2012 by soil cover and woody debris types.

Species	LFH Mineral Soil Mix			Peat		
	Populus tremuloides	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Achillea millefolium L.	+	+	+	+	+	+
Agrostis scabra Willd.	+	+	+	+	+	+
Agrostis stolonifera L.	+	-	+	-	-	-
Arctostaphylos uva-ursi (L.) Spreng.	-	-	-	-	+	+
Aster sp.	-	-	-	+	-	-
Beckmannia syzigachne (Steud.) Fern.	-	+	-	-	-	-
Betula papyrifera Marsh.	-	-	-	+	+	-
Bromus ciliatus L.	+	+	+	+	-	+
Bromus inermis Leyss.	+	-	+	+	+	-
Calamagrostis canadensis (Michx.) Beauv.	+	+	+	+	+	+
Carex aenea Fern.	+	+	+	+	+	+
Carex aurea Nutt.	+	+	+	+	-	+
Carex backii Boott	+	+	-	-	-	-
Carex bebbii Olney ex Fern.	-	+	-	-	-	-
Carex deflexa Hornem.	-	-	+	-	-	-
Carex disperma Dewey	-	-	-	+	+	+
Carex macloviana d'Urv.	-	-	-	+	-	-
Carex norvegica Retz.	+	+	+	+	+	+
Carex siccata Dewey	-	-	-	-	-	+
Carex sp.	+	+	+	+	+	+
Cerastium nutans Raf.	+	-	+	-	-	+
Cerastium sp.	-	-	-	+	-	-
Chenopodium album L.	+	+	+	-	+	-

Scientific names and authorities as per ACIMS (2013) and the USDA plant database (2013).

Table 3.11. Presence (+) absence (-) of plant species, excluding bryophytes, in 2011 and 2012 by soil cover and woody debris types (continued).

	LFH Mineral Soil Mix			Peat		
Species	*Populus tremuloides*	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Cinna latifolia (Trev. ex Goepp.) Griseb.	+	-	-	-	-	-
Cornus canadensis L.	+	+	+	-	+	+
Corydalis sempervirens (L.) Pers.	-	-	+	-	-	-
Crepis tectorum L.	+	+	+	+	+	+
Deschampsia cespitosa (L.) Beauv.	-	-	+	+	-	+
Dracocephalum parviflorum Nutt.	-	+	-	-	+	-
Elymus hirsutus J. Presl.	+	+	+	+	-	-
Elymus trachycaulus (Link) Gould ex Shinners	+	+	+	+	+	+
Elytrigia repens (L.) Gould	+	+	+	+	+	+
Epilobium angustifolium (L.) Holub.	+	+	+	+	+	+
Epilobium ciliatum Raf.	+	+	+	+	+	+
Equisetum arvense L.	+	+	+	+	+	+
Equisetum pratense Ehrh.	+	-	-	+	+	+
Equisetum scirpoides Michx.	-	+	-	+	+	+
Equisetum sylvaticum L.	+	+	+	+	+	+
Erigeron canadensis (L.) Cronq.	+	+	+	+	+	+
Eurybia conspicua (Lindl.) Nesom	+	-	-	-	-	-
Fragaria vesca L.	+	-	+	+	-	+
Fragaria virginiana Duchesne	+	+	+	+	+	+
Galium boreale L.	+	+	+	+	-	-
Galium triflorum Michx.	+	+	-	-	-	+
Gentianella amarella (L.) Boerner	+	-	+	+	+	+

Scientific names and authorities as per ACIMS (2013) and the USDA plant database (2013).

Table 3.11. Presence (+) absence (-) of plant species, excluding bryophytes, in 2011 and 2012 by soil cover and woody debris types (continued).

	LFH Mineral Soil Mix			Peat		
Species	*Populus tremuloides*	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Geranium bicknellii Britt.	+	+	+	+	+	+
Hieracium sp.	-	-	-	+	-	-
Hordeum jubatum L.	+	+	+	+	+	+
Kochia scoparia (L.) A.J. Scott	-	-	+	+	+	-
Lathyrus ochroleucus Hook.	+	+	+	+	+	+
Lathyrus venosus Muhl. ex Willd.	+	+	+	-	+	+
Lepidium densiflorum Schrad.	-	-	-	+	-	-
Leymus innovatus (Beal) Pilger	+	+	+	+	+	+
Lonicera villosa (Michx.) Schult.	-	-	+	-	-	-
Machaeranthera canescens (Pursh) Gray	-	-	-	-	+	-
Maianthemum canadense Desf.	-	-	+	-	-	-
Medicago sativa L.	-	+	-	-	-	+
Melilotus alba Medik.	-	+	-	+	+	+
Melilotus sp.	-	+	-	+	+	+
Mertensia paniculata (Ait.) G. Don	+	+	+	+	+	+
Moehringia lateriflora (L.) Fenzl	+	+	+	-	+	+
Oryzopsis pungens (Torr. ex Spreng.) Dorn	-	-	-	-	-	+
Petasites frigidus var. *frigidus* (L.) Fries	-	-	-	+	+	-
Petasites frigidus var. palmatus (Ait.) Cronq.	+	+	+	+	+	+
Petasites sagittatus (Pursh) A. Gray	-	-	-	+	-	-
Picea glauca (Moench) Voss	-	+	-	-	+	-
Picea mariana (P. Mill.) B.S.P.	-	+	-	-	+	-
Poa palustris L.	+	+	+	+	+	+

Scientific names and authorities as per ACIMS (2013) and the USDA plant database (2013).

Table 3.11. Presence (+) absence (-) of plant species, excluding bryophytes, in 2011 and 2012 by soil cover and woody debris types (continued).

Species	LFH Mineral Soil Mix			Peat		
	Populus tremuloides	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Poa pratensis L.	+	+	+	+	+	+
Poa sp.	-	-	-	-	+	-
Polygonum aviculare L.	-	-	-	+	+	+
Polygonum lapathifolium L.	-	-	-	+	-	-
Populus balsamifera L.	+	+	+	+	+	+
Populus tremuloides Michx.	+	+	+	+	+	+
Potentilla fruticosa (Pursh) Kartesz	-	+	+	+	-	-
Potentilla norvegica L.	+	+	+	+	+	+
Ribes glandulosum Grauer	-	-	+	-	-	-
Ribes hudsonianum Richards.	+	+	+	+	+	+
Ribes lacustre (Pers.) Poir.	-	+	+	+	+	-
Ribes oxyacanthoides L.	+	+	+	+	+	+
Ribes triste Pallas	-	+	-	-	-	-
Rosa acicularis Lindl.	+	+	+	+	+	+
Rubus idaeus L.	+	+	+	+	+	+
Rubus pubescens Raf.	+	+	+	+	+	+
Rumex triangulivalvis (Danser) Rech. f.	-	-	-	+	+	+
Salix candida Fluegge ex Willd.	-	-	+	-	-	-
Salix exigua Nutt.	-	-	-	+	+	+
Salix myrtillifolia Anderss.	-	+	-	+	+	+
Salix scouleriana Barratt ex Hook.	-	-	-	+	-	-
Salix sp.	+	+	+	+	+	+
Salsola kali L.	-	+	-	+	+	+

Scientific names and authorities as per ACIMS (2013) and the USDA plant database (2013).

Table 3.11. Presence (+) absence (-) of plant species, excluding bryophytes, in 2011 and 2012 by soil cover and woody debris types (concluded).

	LFH Mineral Soil Mix			Peat		
Species	*Populus tremuloides*	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Senecio pauperculus (Michx.) A. & D. Love	-	-	+	+	+	+
Shepherdia canadensis (L.) Nutt.	-	-	+	-	+	+
Solidago canadensis L.	+	+	+	+	+	+
Stellaria longifolia Muhl. ex Willd.	+	+	+	+	+	+
Symphyotrichum ciliolatum Lindl. A.& D. Löve	+	+	+	+	+	+
Symphyotrichum puniceum (L.) A.& D. Löve	-	-	+	-	+	+
Taraxacum officinale G.H. Weber ex Wiggers	+	+	+	+	+	+
Trientalis borealis Raf.	+	+	+	-	-	+
Trifolium sp.	-	+	-	-	-	-
Urtica dioica L.	+	+	+	+	+	+
Vicia americana Muhl. ex Willd.	+	+	+	+	+	+
Viola adunca Sm.	-	-	+	-	-	-
Viola renifolia Gray	+	+	+	-	+	-

Scientific names and authorities as per ACIMS (2013) and the USDA plant database (2013).

Table 3.12. Mean percent cover of woody debris per 1 m^2 in 2008 by soil cover and woody debris types.

Size Class	LFH Mineral Soil Mix		Peat Mineral Soil Mix	
	Populus tremuloides	*Picea mariana*	*Populus tremuloides*	*Picea mariana*
Fine	1.9 (0.2)	12.2 (1.8)	1.2 (0.1)	5.3 (1.7)
Small	2.4 (0.3)	4.3 (0.7)	1.7 (0.4)	3.1 (0.7)
Medium	4.6 (0.3)	5.7 (0.5)	5.5 (1.1)	8.6 (1.5)
Large	1.3 (0.5)	0.3 (0.2)	3.5 (1.2)	1.7 (0.3)
Total	10.2 (0.9)	22.4 (2.1)	11.8 (2.2)	18.7 (3.2)

Adapted from Brown 2010.
Significance was not determined for size classes and total cover.
Total cover may not equal the sum of individual size classes due to rounding of the means.

Table 3.13. Mean percent cover of woody debris per 1 m^2 in 2011 by soil cover and woody debris types.

Size Class	LFH Mineral Soil Mix			Peat Mineral Soil Mix		
	Populus tremuloides	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Fine	0.1 (0.0)	0.4 (0.1)	0.0 (0.0)	0.1 (0.0)	1.7 (0.4)	0.1 (0.1)
Small	1.0 (0.3)	2.0 (0.4)	0.3 (0.2)	1.4 (0.5)	2.8 (0.3)	0.1 (0.0)
Medium	8.0 (1.7)	8.0 (1.5)	0.6 (0.2)	8.5 (1.2)	10.7 (0.7)	0.0 (0.0)
Large	1.8 (0.8)	0.4 (0.3)	0.0 (0.0)	4.9 (1.7)	1.2 (0.6)	0.0 (0.0)
Total	11.0 (1.3)$^{B/a}$	10.8 (1.5)$^{B/b}$	0.9 (0.3)$^{A/c}$	14.9 (1.5)$^{A/b}$	16.3 (1.0)$^{A/a}$	0.2 (0.1)$^{B/c}$

Numbers are means followed by standard errors in brackets, n = 6.
Upper case letters indicate significant differences between soil covers and lower case letters indicate significant differences between woody debris types at $p < 0.05$.
Significance was not determined for size classes.
Total cover may not equal the sum of individual size classes due to rounding of the means.

Table 3.14. Mean percent cover of woody debris per 1 m^2 in 2012 by soil cover and woody debris types.

Size Class	LFH Mineral Soil Mix			Peat Mineral Soil Mix		
	Populus tremuloides	*Picea mariana*	Control	*Populus tremuloides*	*Picea mariana*	Control
Fine	0.1 (0.0)	0.5 (0.2)	0.0 (0.0)	0.4 (0.2)	1.3 (0.4)	0.1 (0.0)
Small	1.0 (0.2)	2.4 (0.4)	0.1 (0.1)	1.8 (0.3)	3.4 (0.3)	0.1 (0.0)
Medium	8.2 (0.8)	9.6 (0.7)	0.2 (0.1)	9.3 (0.9)	10.4 (1.2)	0.0 (0.0)
Large	0.8 (0.5)	0.2 (0.2)	0.0 (0.0)	2.2 (0.9)	0.9 (0.3)	0.0 (0.0)
Total	10.3 (0.9)^{b}	12.9 (0.8)^{a}	0.4 (0.2)^{c}	13.8 (1.2)^{b}	16.0 (1.5)^{a}	0.2 (0.1)^{c}

Numbers are means followed by standard errors in brackets, n = 6.
Lower case letters indicate significant differences between woody debris types at $p < 0.100$.
Significance was not determined for size classes.
Total cover may not equal the sum of individual size classes due to rounding of the means.

Table 3.15. Mean percent canopy cover of vegetation growth forms on LFH mineral soil mix by woody debris type for size class assessments.

Parameter	*Populus tremuloides*				*Picea mariana*			
	Fine Quadrat	Small Quadrat	Medium Quadrat	Large Quadrat	Fine Quadrat	Small Quadrat	Medium Quadrat	Large Quadrat
Forb	14.8 (2.5)	17.7 (7.0)	14.9 (3.5)	21.3 (4.7)	21.4 (5.6)	14.6 (2.3)	11.0 (2.4)	17.7 (3.0)
Graminoid	5.7 (1.2)	7.7 (0.9)	5.9 (1.3)	5.9 (1.1)	6.0 (2.7)	7.0 (1.1)	5.1 (1.0)	6.3 (0.7)
Shrub	14.0 (5.7)	15.8 (4.3)	20.5 (5.7)	16.8 (3.3)	18.5 (3.3)	21.9 (5.4)	23.0 (5.3)	21.9 (5.1)
Tree	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Bryophyte	7.0 (1.6)	0.5 (0.3)	0.1 (0.1)	0.0 (0.0)	0.2 (0.2)	0.4 (0.3)	0.0 (0.0)	2.0 (0.9)
Total	31.0 (4.9)	35.4 (5.2)	38.4 (5.5)	41.8 (5.6)	41.4 (3.6)	38.2 (4.8)	37.3 (4.5)	43.5 (3.8)

Numbers are means followed by standard errors in brackets, n = 6.
Significance was not determined for size classes.

Table 3.16. Mean percent canopy cover of vegetation growth forms on peat mineral soil mix by woody debris type for size class assessments.

Parameter	*Populus tremuloides*				*Picea mariana*			
	Fine Quadrat	Small Quadrat	Medium Quadrat	Large Quadrat	Fine Quadrat	Small Quadrat	Medium Quadrat	Large Quadrat
Forb	18.4 (3.5)	25.1 (5.8)	15.8 (2.4)	25.3 (5.3)	22.2 (5.4)	24.2 (1.5)	18.4 (3.4)	21.3 (4.1)
Graminoid	3.2 (1.8)	1.0 (0.3)	2.9 (1)	1.2 (0.3)	0.9 (0.4)	2.5 (0.9)	1.7 (0.9)	1.1 (0.3)
Shrub	7.2 (3.1)	3.4 (2.8)	8.1 (3.3)	8.4 (2.6)	5.9 (1.8)	7.4 (2.4)	14.0 (5.2)	5.7 (0.8)
Tree	5.1 (4.2)	0.5 (0.5)	1.5 (1.5)	5.3 (5.3)	0.8 (0.8)	1.0 (0.7)	1.2 (1.2)	0.2 (0.2)
Bryophyte	12.8 (4.5)	20.6 (9.9)	22.3 (7.1)	7.0 (3.4)	11.4 (8.7)	14.0 (6.2)	12.5 (3.8)	28.6 (6.3)
Total	29.6 (4.9)	26.1 (4.7)	26.9 (1.9)	38.3 (1.8)	27.0 (5.6)	29.3 (2.2)	32.3 (3.3)	21.8 (4.4)

Numbers are means followed by standard errors in brackets, n = 6.
Significance was not determined for size classes.

Table 3.17. Mean percent ground cover on LFH mineral soil mix by woody debris type for size class assessments.

Parameter	*Populus tremuloides*				*Picea mariana*			
	Fine Quadrat	Small Quadrat	Medium Quadrat	Large Quadrat	Fine Quadrat	Small Quadrat	Medium Quadrat	Large Quadrat
Vegetation	6.0 (0.7)	7.5 (2.0)	7.6 (1.4)	6.8 (1.1)	7.0 (1.9)	6.8 (1.1)	5.5 (0.8)	7.1 (0.6)
Bare	1.0 (0.8)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.2 (0.2)	0.8 (0.5)	0.2 (0.2)
Litter	75.3 (4.2)	79.6 (3)	68.8 (1.1)	70.4 (2.2)	72.8 (3.0)	78.6 (2.0)	64.3 (3.8)	67.8 (2.4)
Fine Woody Debris	5.5 (1.3)	1.9 (1.8)	0.3 (0.2)	0.0 (0.0)	9.1 (2.1)	1.6 (1.2)	0.7 (0.4)	0.1 (0.1)
Small Woody Debris	3.4 (1.9)	10.5 (1.6)	3.3 (2.9)	0.1 (0.1)	4.8 (2.4)	10.3 (1.7)	3.6 (2.3)	1.9 (0.7)
Medium Woody Debris	0.0 (0.0)	0.0 (0.0)	17.5 (3.7)	4.9 (4.9)	0.4 (0.4)	0.0 (0.0)	21.2 (5.3)	6.8 (5.0)
Large Woody Debris	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	15.9 (3.3)	5.8 (5.8)	0.0 (0.0)	0.0 (0.0)	13.6 (3.6)
Total Woody Debris	10.6 (2.7)	12.4 (2.1)	22.6 (1.7)	21.7 (2.7)	16.1 (2.3)	13.9 (2.5)	28.8 (3.3)	22.0 (2.6)

Numbers are means followed by standard errors in brackets, n = 6.
Significance was not determined for size classes.

Table 3.18. Mean percent ground cover on peat mineral soil mix by woody debris type for size class assessments.

Parameter	*Populus tremuloides*				*Picea mariana*			
	Fine Quadrat	Small Quadrat	Medium Quadrat	Large Quadrat	Fine Quadrat	Small Quadrat	Medium Quadrat	Large Quadrat
Vegetation	7.9 (2.1)	8.3 (2.2)	7.1 (1.4)	7.2 (1.6)	6.4 (1.8)	7.5 (0.8)	6.3 (1.4)	5.2 (1.6)
Bare	1.7 (1.7)	7.8 (4.7)	3.0 (2.2)	1.2 (0.8)	1.0 (0.6)	3.5 (1.5)	1.2 (0.7)	5.2 (1.5)
Litter	69.5 (6.5)	51.8 (12.7)	41.7 (8.8)	43.8 (8.9)	51.3 (3.5)	62.3 (7.2)	49.4 (4.4)	39.2 (7.2)
Fine Woody Debris	4.7 (0.9)	0.0 (0.0)	0.3 (0.2)	0.0 (0.0)	12.1 (2.0)	1.1 (0.4)	0.2 (0.2)	0.3 (0.3)
Small Woody Debris	2.4 (0.9)	9.5 (1.2)	1.1 (0.8)	0.8 (0.4)	4.5 (2.0)	9.5 (1.8)	1.4 (0.7)	1.6 (0.9)
Medium Woody Debris	0.0 (0.0)	0.0 (0.0)	21.8 (2.1)	1.6 (1)	0.0 (0.0)	0.5 (0.5)	28.3 (1.7)	3.3 (1.6)
Large Woody Debris	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	24.4 (2.7)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	15.2 (2.6)
Total Woody Debris	7.1 (1.7)	9.6 (1.2)	23.3 (2.7)	26.8 (3.2)	16.6 (3.3)	11.1 (1.5)	29.8 (2.1)	20.4 (2.6)

Numbers are means followed by standard errors in brackets, n = 6.
Significance was not determined for size classes.

Table 3.19. Mean woody debris volume by soil cover and woody debris types for size class assessments.

		LFH Mineral Soil Mix		Peat Mineral Soil Mix	
Volume (m^3/ha)	Quadrat Size	*Populus tremuloides*	*Picea mariana*	*Populus tremuloides*	*Picea mariana*
For Quadrat Size Class	Fine	0.006	0.009	0.005	0.010
	Small	0.032	0.031	0.023	0.726
	Medium	0.580	0.582	0.532	0.725
	Large	1.264	0.917	1.651	0.139
Total in Quadrat	Fine	0.013	0.022	0.008	0.018
	Small	0.032	0.032	0.023	0.818
	Medium	0.583	0.606	0.546	0.737
	Large	1.265	0.995	1.688	0.140

Numbers are means followed by standard errors in brackets, n = 6.
Volume for quadrat size class is the volume of the size class of woody debris that the quadrat was designated for. For example, volume for quadrat size class of the fine woody debris quadrat would include the volume of only fine woody debris pieces recorded and would not include the volume of any small, medium or large pieces, even if they were found in that quadrat.
Total volume in quadrat is the total volume of woody debris pieces of all size classes, regardless of if it is a fine, small, medium or large quadrat.

CHAPTER IV. SYNTHESIS AND FUTURE RESEARCH

1. RESEARCH SUMMARY

1.1 Overview

The study area was constructed November 2007 to February 2008 on an overburden dump at the Suncor Energy Inc. mine, approximately 30 km north of Fort McMurray. Six treatment combinations consisted of no woody debris or woody debris from *Picea mariana* (P. Mill.) B.S.P. (black spruce) or *Populus tremuloides* Michx. (trembling aspen) mixed wood forests on LFH mineral soil mix and peat mineral soil mix covered substrates. Two rows of plots with three replicates of each treatment made a total of 36 plots. Half the plots had LFH mineral soil mix (20 cm), over 30 cm of B and C mix horizon subsoil and 100 cm of clean overburden. The other half had peat mineral soil mix (30 cm), over 100 cm of clean overburden. Mean woody debris cover for *Populus tremuloides* mixed wood treatments after construction was 11 %; *Picea mariana* mean was 20 %. Woody debris size classes were fine woody debris with diameter less than 2 cm, small woody debris with diameter 2 to 5 cm, medium woody debris with diameter 5 to 15 cm and large woody debris with diameter greater than 15 cm.

The overall objective of this research was to evaluate ecological effects of using woody debris as an amendment to facilitate reclamation of disturbed landscapes in the Athabasca Oil Sands Region. Vegetation cover, vascular and non vascular species composition, richness, diversity woody plant density and select soil chemical and physical properties were evaluated in years four and five after reclamation. Woody debris volume, size class and cover were assessed to determine optimal application rates for oil sands reclamation. Study area slope and aspect were characterized to determine correlations to vegetation parameters impacted by the row affect. Woody debris cover and vegetation and soil parameters were compared to data from 2008 and 2009 (Brown 2010) to determine differences over time.

1.2 Woody Debris And Soil Cover Type Impacts On Select Soil Properties

Soil chemical and physical properties were often significantly affected by soil cover type. Woody debris did not impact soil chemical and physical properties as much as soil cover type. LFH mineral soil mix had significantly higher silt content, available phosphorus, available potassium, total inorganic carbon and carbon to nitrogen (C:N) ratio than peat mineral soil mix.

Peat mineral soil mix had significantly higher clay content, available sulfate, pH, sodium adsorption ratio and electrical conductivity than LFH mineral soil mix. Available potassium, C:N ratio, electrical conductivity and sodium adsorption ratio increased under both soil covers from 2009 to 2011. Available sulfate did not differ between years in peat mineral soil mix, but increased significantly with time in LFH mineral soil mix. Significant differences in several chemical and physical soil properties are attributed to source parent material and proportions of mixed LFH and peat layers with mineral horizons salvaged below.

Woody debris type and size class moderated soil surface temperature throughout the study. In the years one and two following application of woody debris, ranges in daily, weekly and monthly soil temperatures were significantly greater under small woody debris and controls than large woody debris, with fluctuations decreasing in years three, four and five. Soil cover type played an important role in moderating soil volumetric water content. Peat mineral soil mix had higher daily, weekly and monthly means and greater mean and extreme fluctuations in soil water content than LFH mineral soil mix.

Thus reclamation soil cover mixes can influence site soil properties and subsequently the succession of ecosystem recovery. Therefore, reclamation areas should be managed based on potential site conditions associated with various soil cover mixes chosen for the intended end land use for the site after reclamation. The overall effects of woody debris may start out very positive and then its influence may decrease in the early stages of reclamation, as its role begins to interact with that of the surrounding vegetation. However, woody debris continues to stabilize soil surface temperatures and site conditions and is essential to early ecosystem regeneration. Little decomposition of woody debris is occurring in years four and five after its application, but as reclamation continues and woody debris decay reaches mid to advanced stages, effects of woody debris will likely have an accelerating influence on soil nutrient cycling processes with inputs of nutrients to the soil.

1.3 Woody Debris And Soil Cover Type Impacts On Vegetation

Although woody debris continues to influence plant community composition and development in years four and five after reclamation, soil cover type affected plant community properties more than woody debris. Only tree, total woody debris, graminoid and introduced species covers and woody debris volume had woody debris as a significant factor contributing to treatment differences. Bare ground, forb, shrub, tree, bryophyte and introduced species covers and introduced species richness were significantly higher in peat mineral soil mix than LFH mineral soil mix in 2011. Litter, total canopy, graminoid and native species covers were higher on LFH mineral soil mix than peat mineral soil mix in 2011. Bare ground, shrub, bryophyte, and introduced species covers and introduced species and total species richness were significantly higher on peat mineral soil mix than LFH mineral soil mix in 2012. Litter, total canopy, and graminoid covers and woody plant density were higher on LFH mineral soil mix than peat mineral soil mix in 2011. Species diversity did not differ significantly between soil cover and woody debris types in 2011 and 2012. Species diversity increased from 2011 to 2012, suggesting succession is occurring on the study area, despite minimal inputs after initial site construction. Block was a significant factor for many vegetation parameters. Slope and aspect did not correlate with any vegetation parameters except for native species richness.

Most vegetation parameters either increased or decreased significantly over five growing seasons. Shrub cover, litter cover, native species richness and total species richness increased, while bare ground cover and introduced species cover decreased, indicating desirable changes in the plant community over time. Bryophyte cover, native species cover, tree cover, and total canopy cover changed between years, but the changes varied depending on soil cover. Woody plant density did not significantly change between years.

A total of 119 vascular and non vascular species were found on the site, which is likely an underestimation due to a number of bryophytes and vascular plants, including *Salix* spp. and *Carex* spp. not being able to be identified to the species level. Most species are early successionals that occur in naturally and anthropogenically disturbed areas, but there are several species found in 2011 and 2012, but not found in 2008 and 2009, that can be considered to be mid to late successional. The presence of these species suggests that reclamation is likely following a successional trajectory to a later seral plant community.

Woody debris volume and cover had no negative effects on plant community development. Current recommended volume application rates of 60 to 100 m^3/ha may be high since approximate application rates of 50 to 75 m^3/ha provided positive ecological effects for reclamation. Volume may not likely be as important as distribution of size classes and placement of the material. Although the lower coverage on the SE dump continues to exhibit positive effects on the plant community, higher coverage rates may be needed early on in reclamation to promote microsite influences and soil protection from wind and water erosion. These results show a continual positive relationship between woody debris and soil cover and soil and vegetation development in year five post reclamation, demonstrating the promotion of ecological succession on this disturbed landscape.

2. APPLICATIONS FOR RECLAMATION

LFH mineral soil mix is the preferred cover soil to peat mineral soil mix for upland reclamation sites to promote native plant community development in the long term (McMillan 2005, Mackenzie 2006, Mackenzie and Naeth 2010, Brown 2010, Hahn 2012, Mackenzie and Quideau 2012, Mackenzie 2012, Archibald 2014). In year five after reclamation, LFH mineral soil mix continues to have positive impacts on chemical and physical soil properties and moderating soil surface temperature. Use of LFH on upland reclaimed areas is highly recommended to promote quick plant community establishment through provision of suitable soil materials with a seed bank and plant propagules conducive to an upland end land use and micro sites for early plant establishment. Use of peat material would be preferential in lowland areas that conform to the properties of donor soil.

Current management strategies for woody debris in the Athabasca Oil Sands Region includes piling and burning, mulching, rough mulching, breaking logs into chunks and placing non merchantable whole logs (Vinge and Pyper 2013). Recent regulations recognize the ecological value of using woody debris and encourage its use to facilitate reclamation (ESRD 2013). Readily available, potentially wasted woody material can create microsites that increase site variability, and increase plant establishment and survival by providing protection, shade and sequester soil water (Andersson and Hytteborn 1991, Mills and Macdonald 2004, Botting and Fredeen 2006). Woody debris quickens recovery of meso fauna, microorganisms, soil nutrients, soil water and floral diversity. It acts as a seed source, enhances soil formation processes, functions effectively as erosion control and aids in nutrient cycling, particularly in the long term (Harmon et al. 1986, Rambo and Muir 1998, Hély et al. 2000, Ódor and Standovár 2001, Brown 2010, Brown and Naeth 2014). Woody debris acts as habitat and shelter for invertebrates, microorganisms, mammals, and fungus species (Crites and Dale 1998). Application of woody debris in reclamation can help to develop functional and sustainable ecosystems, with relatively little financial implications compared to other used reclamation prescriptions, on a large scale.

Evidence of *Picea mariana* seedlings emerging from cones of woody debris suggests woody debris is a viable propagule source for plant community establishment. Similar to targeting the use of LFH mineral soil mix to upland reclamation areas and peat mineral soil mix to lowland reclamation areas that would allow the seed bank in the soil to thrive in these end land uses, application of specific woody debris species based on the target end land use should be prioritized. Application of woody debris species that corresponds to the same end land use that the material was sourced from (upland, lowland) is important to facilitate the health and survival of seedlings emerging from woody debris propagules. Upland woody debris species such as *Populus tremuloides*, *Pinus banksiana* Lamb. (jack pine) and *Picea glauca* should be applied in combination with LFH mineral soil mix to areas with a target end land use of upland forest. Lowland woody debris species such as *Picea mariana* and *Larix laricina* (Du Roi) K. Koch (tamarack) should be applied with peat mineral soil mix to areas with a target end land use of lowland forest.

Based on visual observations, there is likely little decomposition of woody debris occurring in years four and five after its application, but as reclamation continues, effects of woody debris entering mid to late stages of decay will likely have an accelerating influence on soil nutrient cycling processes. Long term effects of decayed woody debris are expected to increase species diversity, species richness and plant community composition and stimulate soil formation processes. Long term research to evaluate benefits of woody debris applied in mid to late stages of decay would be important to affirm its use for sustainable reclamation.

Volume and cover application rates varied in the study. Current application rates were lower than recommended by Vinge and Pyper (2013), based on a literature review of natural inputs to forest ecosystems in the boreal forest. Current recommended volume application rates of 60 to 100 m^3/ha may be high. Application rates of 50 to 75 m^3/ha are suitable volumes to provide positive ecological effects for reclamation. Volume may not be as important as distribution of size classes and placement of the material. Although 10 to 16 % coverage on the study area continues to exhibit positive effects on the plant community, higher coverage rates may be needed early on in reclamation to promote microsite influences and soil protection from wind and water erosion.

3. STUDY LIMITATIONS

The results from this study are specific to the study area and to the climatic and seasonal conditions they were subject to between the time of establishment in 2008 and the final site assessments conducted in 2012. Treatment designs other than those studied including, but not limited to, different woody debris species and donor ecosites and site types, density of woody debris application, soil cover salvage and application depths and different donor soils may behave differently than those studied here. Results of soil chemical analyses suggest the source of peat mineral soil mix was from a moderate rich fen ecosite. Results may have differed if the source of soil cover material was from bog peat rather than fen peat, due to the inherent chemical differences of the two materials. This study used woody debris species of stands dominated by a single species (*Populus tremuloides*, *Picea mariana*), but many stands in the oil sands regions have mixed tree species that may have different effects if applied for reclamation purposes. The chemical composition of bark, heart wood and sap wood varies by tree species, which can affect decay rates and nutrient inputs from woody debris to soil covers over time. Aspen woody debris used in the study was from an aspen mixed wood stand with approximately 30 % *Picea glauca* (Moench) Voss (white spruce) in the material. This cover type demonstrates effects of specific mixes of woody debris species, but stands that include species such as *Betula papyrifera* Marsh. (paper birch), *Populus balsamifera* L. (balsam poplar) and *Pinus banksiana* may have different long term impacts on reclamation. Management activities different than those applied to the study area including, but not limited to, different fertilizer regimes, different planting prescriptions and different weed management strategies could also yield different results. These differences limit the study conclusions to the specific circumstances surrounding the research project.

Future monitoring of the study area will be confounded by the vegetation surrounding the study area and the proximity of plots to each other despite the 5 m buffer between plots within rows and the 10 m buffer between rows. The research plots are surrounded by a plant community did not have woody debris applied after soil cover placement and as a result, is dominated by early successional species and a higher proportion of invasive species. Impacts of woody debris and soil cover types on vegetation within the plots will not be solely contributed to intra plot factors, meaning plant species that establish can easily disperse onto nearby treatments or can establish on the plots from outside the study area.

Block (treatment rows) was a random factor in the mixed model analysis. Block was considered a significant factor or significant as an interaction with woody debris or soil cover type for several soil and vegetation parameters. The effect of block was evaluated by correlating slope and aspect to parameters that have a significant block effect or significant block interaction. Correlations were not significant and the effect of block was likely due to low sample sizes and inherent variability of the parameter values within the site.

4. FUTURE RESEARCH

- Long term monitoring. Continue monitoring the study area to determine if the effects of woody debris and soil cover type on native plant community and soil development, including nutrient cycling, persist in the long term. Assess at five year intervals (year 10, 15, 20, etc.) until a minimum of 30 years post reclamation to provide important information for stages of succession of the study area.

- Confounding treatment effects. Establish large scale, long term experiments with experimental units several hectares in size to compare confounding effects of treatments in close proximity to each other. Examine the effects of nearby dispersal and encroachment of various vegetation species and the effect vegetation assemblages have on providing shelter and protection to neighbouring treatments.
- Source of species present. Examine if plant species establishing on the study area are from seeds or propagules present in the soil cover type. Determine if plants establish from woody debris propagules, such as cones, or if they are encroaching from nearby undisturbed forests. Assess these data to help determine the need for planting and seeding specific species that are more or less prone to disperse from surrounding areas or regenerate from soil or woody debris propagules.
- Maximum woody debris cover. Evaluate treatments with incremental cover applications to determine at what point negative effects are exhibited in terms of limited space to grow and nutrient limitations. Compare to this study, which assessed mean covers of 10 to 16 %, and with the higher recommended rates by Vinge and Pyper (2013).
- Fertilizer application. Assess what would happen if plots were not fertilized, if fertilizer application stops after a certain period of time and if sites were fertilized for longer periods of time. Use the data to determine effects of fertilizer application on woody debris decay and if rate of decay is slowed or expedited with fertilizer inputs.
- Appropriate end land use for woody debris type. Evaluate if cleared woody debris should be selectively placed based on the source ecosite and site type and corresponding end land use of the reclamation area. Determine whether *Picea mariana* woody debris might be a good amendment to use on low lying areas, since it is generally a lowland species and there is evidence that *Picea mariana* seedlings are emerging from woody debris cones. Determine whether these seedlings have a better survival rate if woody debris type is placed in areas that will support woody debris propagules.
- Microtopography. Determine if other forms of microsites, such as hummocks and rocks, that could be incorporated with woody debris application will produce similar or more positive results than with woody debris alone. Compare research plots with woody debris and hummocks to level plots.

- Woody debris rate of decay. Assess rate of decay in the study area by recording decay class (classes 1 to 5, with 1 being newly fresh and 5 being almost completely decayed according to Yan et al. 2006) in conjunction with collecting vegetation information. Use qualitative and quantitative parameters to evaluate the stage of woody debris decay and designate decay classes for woody debris pieces. Since decay rates may be low, determine if incremental assessments in five year intervals may be sufficient to capture decay stages that could help determine future trends in nutrient cycling and plant community distribution and composition. Determine whether woody debris decay class is a key indicator of ecosystem succession.
- Decayed woody debris application. Determine if adding woody debris in later decay classes has added benefits (effects by age) for vegetation growth.
- Woody debris substrate quality. Evaluate substrate quality and bryophyte community distributions and composition in relation to substrate quality, as bryophyte assemblages are dependent on the quality of woody debris materials.
- Microbial and fungal community development. Assess microbial and fungal community composition of soil and woody debris over time. Determine whether associations with woody debris and various stages of decay indicate the trajectory of ecosystem genesis.
- Bryophyte community development. Identify and assess bryophyte assemblages that develop at later stages of reclamation (10, 20, 30 years). Determine whether as woody debris decay progresses, bryophyte richness and composition increases, as expected.
- Invertebrates. Identify and assess species of invertebrates. Examine distribution of invertebrates and their preference for soil cover type or woody debris type.
- Wildlife utilization. Evaluate the degree of wildlife use at various stages after reclamation and whether the reclamation area attracts a greater abundance and diversity of species not found in other areas of the mine. Determine whether this discloses impacts and hazards associated with wildlife areas amid active industrial developments.
- Tree planting. Compare effects of planting trees next to woody debris with no trees planted and with trees planted randomly throughout. Since woody debris increased microsites for woody plant seedlings to grow in, which vegetation species subsequently grew in close proximity to in the first two years after reclamation (Brown 2010), assess if selectively planting trees next to woody debris increases the health and survival of planted trees that would otherwise be randomly placed in a woody debris treatment.
- Erosion and erosion control. Quantify soil loss by water erosion in reclamation areas with woody debris applied to help determine if different strategies for direction of woody debris

placement (horizontally, vertically, randomly) on a slope can improve the function of woody debris as an erosion control agent.

- Hydrological characterization. Evaluate surface and subsurface water flow of the study area to see if it can explain differences in the vegetation community and species distribution as vegetation changes in relation to topography can be influenced by hydrology.

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APPENDIX A. CALIBRATION EQUATIONS FOR SOIL VOLUMETRIC WATER CONTENT FROM CHAPTER II

The HOBO system outputs volumetric water content data calculated from a linear default equation for sandy loam soils (Brown 2010). A calibration equation was needed to calibrate HOBO data to accurately represent the peat mineral soil mix and LFH mineral soil mix covers used on the research site in year four post reclamation. In a previous study by Brown (2010), O'Kane Consultants Inc. formed second order polynomial equations based on their experience in the oil sands and on year long data collected from this study.

Maximum and minimum recorded values were used to approximate field capacity and residual water content (Brown 2010). A default equation was used on the raw volumetric water content data to extract the raw mV data, followed by a material specific equation that was used to calibrate the raw mV data into volumetric water content data specific to soil cover type. Equations are as follows.

(a) LFH mineral soil mix

Default equation: mV data = (raw VWC – B) / M

Where VWC = volumetric water content, B = -0.327, M = 0.000682

Material Specific Equation

Calibrated VWC = C2 * (mV data)^2 + C1 * (mV data) + C0

Where C2 = -0.00000051, C1 = 0.00144, and C0 = -0.54

(b) Peat mineral mix

Default equation: mV data = (raw VWC – B) / M

Where VWC = volumetric water content, B = -0.327, M = 0.000682

Material Specific Equation

Calibrated VWC = C2 * (mV data)^2 + C1 * (mV data) + C0

Where C2 = -0.00000198, C1 = 0.00423, and C0 = -1.5718

APPENDIX B. PRECIPITATION AND TEMPERATURE METEOROLOGICAL DATA FROM CHAPTERS II AND III

Table B.1. Total accumulated precipitation (mm) and long term climate normals at the Mildred Lake weather station, 13 km northwest of the southeast dump 2008-2012.

Season	2008	2009	2010	2011	2012	Long Term Normal
January	14.6	10.2	17.6	20.4	18.5	20.4
February	28.2	13.1	22.3	36.0	21.5	37.5
March	49.7	36.0	35.1	46.7	55.2	55.9
April	75.7	59.3	101.9	53.0	76.1	76.6
May	82.2	63.2	134.1	64.1	97	112.5
June	159.0	133.3	147.6	113.4	156.6	178.2
July	223.7	156.3	210.2	146.8	244.4	254.4
August	328.3	212.5	308.1	170.9	279.8	315.3
September	346.6	223.6	359.0	195.0	381.5	363.1
October	368.7	251.6	365.3	207.0	436.5	387.9
November	402.8	269.3	383.8	220.0	463.8	410.7
December	423.9	283.0	407.3	241.3	483.9	431.9

Values for the long term normal and each month within the year is the accumulated precipitation on the last day of each month.
Long term normals were calculated for the period from 1961 to 2008.
Data from the AgroClimatic Information Service Current and Historical Alberta Weather Station Data Viewer (AARD 2014).

Table B.2. Mean air temperature (°C) and long term climate normals at the Mildred Lake weather station, 13 km northwest of the southeast dump 2008-2012.

Season	2008	2009	2010	2011	2012	Long Term Normal
January	-16.6	-18.0	-15.4	-18.6	-13.0	-19.3
February	-16.8	-14.9	-8.8	-15.0	-10.2	-14.5
March	-8.0	-10.1	-0.4	-10.0	-5.3	-7.8
April	-0.0	3.4	6.1	3.1	3.2	2.6
May	11.7	8.2	10.1	12.8	12.5	9.7
June	17.0	15.5	16.8	15.7	16.9	14.6
July	18.1	17.3	18.5	18.4	20.2	16.8
August	17.3	16.7	15.9	17.3	18.1	15.2
September	10.2	14.6	9.1	14.1	12.8	9.5
October	6.1	1.5	5.9	5.7	0.6	2.9
November	-3.2	-2.7	-7.0	-7.7	-11.0	-8.4
December	-21.0	-17.5	-16.5	-7.8	-19.7	-16.7

Values for the long term normal and each month within the year is the mean temperature for each month.
Long term normals were calculated for the period from 1961 to 2008.
Data Data from the AgroClimatic Information Service Current and Historical Alberta Weather Station Data Viewer (AARD 2014).