Water availability and understory influence on tree growth in reclaimed forest ecosystems, Athabasca oil sands region, Alberta, Canada

by

Jason David House

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

Master of Science
in
Soil Science

Department of Renewable Resources
University of Alberta

ABSTRACT

Reclaimed forest ecosystems in the Athabasca oil sands region (AOSR) have limiting factors to growth that can result in poor tree performance, as indicated by stunted growth, foliar discolouration and needle dropping, and ultimately threaten reclamation success. Indicators of reclamation success are understory plant community development and productive tree growth. Water availability as well as soil properties such as soil organic carbon content were investigated as limiting factors to growth on previously reclaimed forest ecosystems planted with lodgepole pine (*Pinus contorta)* and white spruce (*Picea glauca*). Lodgepole pine and white spruce were planted in peat-mineral mix (PMM) cover soil and had tailings sand (TS) and overburden (OB) substrates, respectively, below the cover soil. Composite samples of PMM, peat, OB and TS were used to calibrate time domain reflectometers in the laboratory and to develop a soil moisture retention curve so water availability could be measured in the field. Understory plant communities were examined for composition, cover and foliar nutrient concentrations. On the TS plots, total understory layer cover was negatively correlated to mean PMM water availability and on the OB plots, total understory layer cover was positively correlated to PMM soil carbon and nitrogen content. Understory nutrient concentrations in both TS and OB reclaimed forest ecosystems were related to water availability but only on OB sites were understory foliar nutrient concentrations related to tree growth. Tree growth was limited by water availability in 2011, a drier than average year; tree growth was significantly correlated with mean PMM water availability and mean PMM water availability was also correlated with PMM soil organic carbon content on TS plots. Thus, sites with high organic matter content or thick PMM layers had substantially greater water availability and, therefore, more tree growth. On OB plots, mean PMM water availability was not correlated to tree growth, but tree growth was significantly

correlated with soil organic carbon content, indicating that other factors are more limiting than water availability on the OB plots. Reclamation practioners should consider re-constructing sites with thick cover soils and high soil organic carbon contents (i.e., more peat) so that the rooting zone of the soil can hold more water for root uptake., reducing the risk of low water availability and likely improving tree and understory growth in reclaimed forest ecosystems.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr. Scott X. Chang for his support and guidance, without it, I probably would have never finished. The skills and knowledge I gained working in his lab spring-boarded me into my professional career. I also thank my supervisory committee members, Dr. Philip G. Comeau and Dr. Miles F. Dyck for their guidance and teaching along the way too. The assistance I received from the other students and helpers in our lab was incredible. I would like to thank Min Duan, Ghulam Murtaza, Jinhyeob Kwak and Kangho Jung, Lei Sun, Xiopeng Li, Qiting Chen, Jenna Zee, Aggy Hery and Isabel Fodor for their help in the field and in the laboratory. I would also like to thank Stantec Consulting Ltd., especially Jeff Battigelli, Murray Riddell and Ivan Whitson, for their encouraging and providing me with ample opportunities to work on my thesis

Financial support was provided by the Environmental Reclamation Research Group (ERRG) of the Canadian Oil Sands Network for Research and Development (CONRAD) with contributions from Suncor Energy Inc., Canadian Natural Resources Limited, and Shell Canada Energy. Thank you to the reclamation staff at Suncor Energy Inc. for providing access to the study area and support while we were onsite.

I would like to thank my family. My parents, brother and sister always encouraged me throughout the process to keep going and not give up. I thank my son, Xavier, for being awesome. Lastly, I owe my biggest thanks to my wife, Kristen. She has been along my side this entire journey and her patience and support made this opportunity to complete my Master's program possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Chapter 1 General Introduction

1.0 Introduction

Alberta's oil sand deposits, including the Athabasca, Cold Lake, Peace River and Wabasca deposits, contain the world's second largest oil source (Fung and Macyk, 2000). The Athabasca deposit is the largest and is the only deposit that is accessible by surface mining (Fung and Macyk, 2000). The surface mineable area in the Athabasca oil sands region (AOSR) is 4,800 km^2 and to date, 844 km^2 has been affected by oil sands mining (Alberta Environment, 2013). Of the affected area, 90.7% is presently disturbed while 9.3% is at some stage of reclamation, ranging from having reconstructed soils placed to being certified reclaimed (Alberta Environment, 2013). In the future, it is reasonable to expect these unconventional oil deposits will experience much development and extraction because, globally, sources of conventional oil are in decline. Therefore, successful reclamation to these areas is required to mitigate the environmental effects of oil sands development.

1.1 Legislation on land reclamation in Alberta

In the province of Alberta, it is the law that oil sands mines must be reclaimed. Laws regarding reclamation were first established in 1963 when Alberta became Canada's first province to legislate land reclamation with the *Surface Reclamation Act* (Government of Alberta, 1963). This Act was mostly related to land owner concerns regarding well site reclamation (Powter et al., 2012). Since then, other legislation including the *Public Lands Act* (Government of Alberta, 1969) and the *Land Surface Conservation and Reclamation Act* (Government of Alberta, 1973) expanded reclamation requirements to other disturbances such as mining. In 1992, the *Environmental Protection and Enhancement Act* (Government of Alberta, 1992) was legislated to replace the above Acts, as they related to land, air and water (Powter et al., 2012). In this Act, the province for the first time defined reclamation, as related to surface mining, as "the stabilization, contouring, maintenance, conditioning or reconstruction of the surface land; and any other procedure, operation or requirement specified in the regulations". In 1993, the province specified the requirements in the regulations with the *Conservation and Reclamation Regulation* (Government of Alberta, 1993) which states that in order for mining companies to receive a reclamation certificate, disturbed land must be returned to an equivalent land capability. Within the *Conservation and Reclamation Regulation* (Government of Alberta, 1993), equivalent land capability is defined as "the ability of the land to support various land uses after conservation and reclamation that is similar to the ability that existed prior to the activity being conducted on the land, but that the individual land uses may not be identical". This legislation was designed to be flexible for such a large and dynamic province, but industry, stakeholders and the public have had trouble understanding it (Powter et al., 2012). Nonetheless, this legislation provides a framework for land reclamation on disturbed industrial land and specifically, this legislation is followed by Alberta's oil sands industry today. So far, only Syncrude Canada Ltd. has been issued a reclamation certificate in the AOSR for a 1 km^2 area known as Gateway Hill (Government of Alberta, 2013). Also, Wapisiw Look-out, a former tailings pond at Suncor Energy Inc. is the first tailings pond in the AOSR to have been reclaimed (Government of Alberta, 2013).

1.2 Reclamation in the Athabasca oil sands region

The majority of reclamation in the AOSR consists of reclaiming upland forests, and as such, commercial forestry is one of the most common end land uses for land reclamation in the AOSR (Cumulative Environmental Management Association, 2006). However, there has been more focus on wetland and peatland reclamation in recent years (Bhatti and Vitt, 2012; Faubert and Carey, 2014) since 29% of the AOSR is wetlands (Lee and Cheng, 2009). Wetland reclamation is beyond the scope of this research and will not be discussed in detail here.

The process of reclaiming upland forest typically involves: filling the mined pit with a substrate, typically overburden, or mine wastes (i.e., tailings sand), capping the substrate with a cover soil, and establishing vegetation on the cover soil. Due to the abundance of peat in the region, peat-mineral soil mix (PMM) is a commonly prescribed cover soil that consists of salvaged peat and mineral soil from surface mining activities (Rowland et al., 2009). Two of the many attributes that make peat a vital component of the cover soil are: 1) it increases water holding capacity (Moskal et al., 2001) and 2) provides soil nutrients as it slowly decomposes (Hemstock et al. 2010). Native tree and shrub species are planted and understory plant communities develop by seeds and propagule banks in the cover soil material (Mackenzie & Naeth, 2010) and by seed dispersal from surrounding reclaimed and natural areas (Hardy BBT, 1990). Also, understory species are sometimes seeded and/or planted as part of the reclamation prescription (Naeth et al., 2011). The resultant plant communities that form from a combination of direct and inadvertent human actions are examples of novel ecosystems (Hobbs et al., 2006).

1.3 Biophysical characteristics of the Athabasca oil sands region

The AOSR is located within the boreal forest. The boreal forest is circumpolar in the northern hemisphere, covering approximately 11% of Earth's terrestrial surface and containing 25% of our remaining intact forests (Canadian Boreal Initiative, 2009), which makes it one of the largest ecosystems on Earth. In Alberta, the boreal forest covers 54% of the province (Alberta Environmental Protection, 1998). The AOSR is located within the central mixed-wood natural subregion of the boreal forest natural region (Archibald and Beckingham, 1996). Land cover is a mosaic of upland forest, peatlands and lakes. Trembling aspen (*Populus tremuloides*), white spruce [*Picea glauca* (Moench) Voss], and jack pine (*Pinus banksiana*) are the dominant tree species in the upland forests; and black spruce (*Picea mariana*) or tamarak (*Larix laricina*) are the main tree species in the bogs and sedge fens (MacDonald et al., 2012). Soil orders in the AOSR consist of Luvisols, Brunisols, Regosols, Gleysols and Organic soils (Turchenek and Lindsay, 1982). Upland mineral soils are predominantly developed on glacial till, glaciofluvial and eolian parent materials whereas organic soils consist of organic materials (sphagnum moss, sedges, grasses, or tree and shrub remnants) overlying glacial deposits (Thompson et al., 1978). Climate in this region is characterized by short, moderately warm summers and long, cold winters (Bonan and Shugart, 1989). Annual precipitation is 455.5 mm with rainfall and snowfall accounting for 342.2 mm and 113.3 mm, respectively (Environment Canada, 2009).

1.4 Limiting Factors to Plant Growth

Since commercial forestry is a common end land use, reclaiming a productive forest is important to achieving reclamation success. Reclamation practioners face many challenges in establishing productive reclaimed forest ecosystems because, in general, plant growth on these sites, like anywhere else on Earth, is limited by the surrounding environment. If an environmental factor is not optimal for plant growth it will become a limiting factor. The main limiting factors to plant growth are light, temperature, water and nutrition (Havlin et al., 2005). Quantity, quality and duration of light can affect plant growth. Increasing temperature affects plant growth by increasing photosynthesis, respiration and transpiration. Low temperatures can reduce energy use and increase sugar storage, and frost damage can be an issue in the AOSR as well. Temperature also triggers and breaks dormancy in plants signaling the end and beginning of the growing season, respectively. Water affects plant growth in many ways (e.g., it is a key part of photosynthesis and it is a solvent for nutrients moving into the roots and up into the plant). Nutrition affects plant growth because plants need 18 elements for growth. From air and water, plants need carbon, hydrogen and oxygen; the rest of the elements are in the soil solution (nitrogen, phosphorous, potassium, magnesium, calcium, sulfur, iron, zinc, molybdenum, nickel, manganese, boron, copper, cobalt and chlorine) (Havlin et al., 2005). These nutrients are dissolved in soil water and then extracted by roots. These four main factors interact to impose complex limitations to plant growth (Churkina and Running, 1998). Additionally, climate change is impacting plant growth by increasing net primary production which, on the one hand, indicates that it is easing climate-related limiting factors to plant growth (Nemani et al. 2003), but on the other hand, climate change is also increasing drought stress in the AOSR.

In reclaimed forest ecosystems in the AOSR in particular, limiting factors to growth can result in poor tree performance as is indicated by stunted growth, foliar discolouration and needle dropping. It is suspected that the main limiting factors in this area are low nutrient availabilities, specifically nitrogen, phosphorus and potassium (Rowland et al., 2009), high salinity and/or sodicity (Meiers et al., 2011), and hydrophobicity (Moskal et al., 2001). Climate in the Boreal region can also limit tree growth due to short growing season, low growing season temperatures and periodic summer water deficits (Bonan and Shugart, 1989), which can lead to low water availability. Many studies have attempted to address these limiting factors to tree growth in the AOSR by comparing different cover soils (MacKenzie and Naeth, 2010), studying the effect of woody debris addition to cover soils (Brown and Naeth, 2014), describing soil water regimes (Leatherdale et al., 2012), and studying the effects of textural interfaces between reconstructed soil materials on tree growth (Jung et al., 2014). Factors limiting plant growth, however, are site-specific. The aim of this study is to identify what factors are limiting tree growth on some of the older reclaimed forest ecosystems in the AOSR. My research had two foci: 1) to characterize understory plant communities and their relationships with tree performance in a range of plots that constitute a productivity gradient in reclaimed forest ecosystems in the AOSR, and 2) to study water availability as a potential limiting factor for tree growth in reclaimed forest ecosystems in the AOSR. Another graduate student, Min Duan, studied soil nutrient availability and soil salinity/sodicity as potential limiting factors in the same reclaimed forest ecosystems (Duan et al., 2015).

1.5 Thesis structure

The first data chapter examines how substrate and cover soil materials affect novel ecosystem development and how the understory is related to overstory tree growth and associated soil-site factors. The second data chapter examines water availability as a limiting factor to tree growth. More specifically, the research focus is on the effect of soil physical properties on cover soil water availability to see if reclaimed forest ecosystems with poor tree growth are related to poor water availability and/or indicators of water stress.

The research design for this study was *ex post facto*, that is, after-the-fact research. The study was in reclaimed forest ecosystems where land reclamation took place 15 to 30 years ago, located on Suncor Energy Inc. Lease 86/17, near Fort McMurray, Alberta. I chose my plots in existing reclaimed forest ecosystems to represent a gradient of tree performance with tailings sand (TS) or overburden (OB) as the substrate. Some plots had trees with stunted growth, needle discolouration and/or needle dropping, while other ones had trees that were performing relatively well, indicated by vigorous leader growth and dense, green canopy cover. Statistical methods, including linear regression analysis and non-metric multidimensional scaling, were used to investigate potential relationships between tree growth and site variables. However, the relationships I found do not imply cause and effect because it is not possible to know if the limiting factor was included in the analysis. Instead, the results from this research will be useful to create new hypotheses about limiting factors in reclaimed forest ecosystems that can be tested with properly designed experiments. Also, the results from this study should be considered by land reclamation practioners while planning and designing soil covers for future reclamation projects in the AOSR. With greater insight into limiting factors to growth, future reclamation practices that address these limitations may have a greater success reclaiming land disturbed by surface mining and achieving reclamation certification in the AOSR.

2. Chapter 2 Substrate type affected understory plant communities in reclaimed upland forest stands in the Athabasca oil sands region

1.0 Introduction

Plant communities that develop on reconstructed soils following surface mining are examples of novel ecosystems, which are created as a result of deliberate or inadvertent human actions to the natural environment (Hobbs et al., 2006). In forested regions, the goal for reclamation is typically reforestation with commercially valuable tree species (Oil Sands Vegetation Reclamation Committee, 1998) and resultantly most research has focused on the success of planted tree species (Zipper et al., 2011; Carrera-Hernández et al., 2012; Pinno et al., 2012). Less attention has been given to the dynamics of understory plant communities which develop amongst planted tree species. However, more recently regulatory attention has been given to the development of understory plant communities as an indication of reclamation success, rather than just focusing on commercially valuable tree species (Alberta Environment, 2010). Consequently, more research regarding understory plant communities in reclaimed forest ecosystems is being conducted (Mackenzie and Naeth, 2010; Naeth et al., 2011).

Understory plant communities develop via seed and propagule banks in the cover soil material (Mackenzie and Naeth, 2010), seed blown in from surrounding areas (Hardy BBT, 1990), and occasionally via direct seeding and/or planting as part of a reclamation prescription (Naeth, 2011). Moisture and nutrient regimes in reclaimed forest ecosystems dictate plant establishment and factors that affect these regimes include, but are not limited to, cover soil physical and chemical properties, substrate type and overstory cover. As the planted trees grow in reclaimed forest ecosystems, the development of understory communities is also influenced by competition for light and nutrients with the overstory species. In addition, understory vegetation can influence survival and growth of planted trees. Characterizing understory plant communities and investigating factors affecting their development will be useful for land reclamation managers and government regulatory bodies in their decision making processes.

Cover soils in reclaimed forest ecosystems provide the bulk of soil moisture and nutrients for plant establishment, survival and growth, and soil organic matter is one of the most important factors affecting soil quality (Gregorich et al., 1994). Peat-mineral soil mix (PMM) is a cover soil created by mixing peat with mineral soil and is commonly used in land reclamation in the Athabasca oil sands region (AOSR). Peat in PMM increases water holding capacity (Moskal et al., 2001) and its decomposition is the primary source of nutrients for plants (Hemstock et al., 2010). Poor vegetation cover has been correlated with lower soil organic carbon levels in the PMM layer (Burgers, 2005).

A thicker cover soil provides more soil volume for plant roots to extract water and nutrients. Current research shows conflicting results regarding the effect of cover soil thickness on understory plant communities: Purdy and Macdonald (2007) showed that thicker cover soils had higher understory native plant densities and slightly higher understory plant community cover than thinner cover soils; however, Mackenzie and Naeth (2010) found that there was no difference in understory plant community cover between 10 and 20 cm thickness of PMM used as a cover soil. It should be noted that these two studies were conducted on relatively young sites that were 6 years and 18 months old, respectively. The differences between the two studies suggest that the thickness of the cover soil may have a greater effect on understory plant communities once the overstory is established; likely because the demand for soil water and nutrient supply increases as the trees and understory plant communities develop.

The type of substrate material used below the cover soil can affect the soil moisture regime in the cover soil (Jung et al., 2014) and therefore understory plant community establishment. When tailings sand (TS) is the substrate material, the textural interface between it and the cover soil, typically a fine textured material with high organic matter content, creates a capillary barrier that limits water percolation down into the coarser-textured TS substrate (Porro, 2001; Naeth, 2011). This barrier can increase water retention in the cover soil until the soil water potential exceeds the minimum water entry potential of the underlying layer. Then water will percolate into the TS layer (Leatherdale et al., 2011). This benefits vegetative growth because the majority of the roots are located in the PMM where soil water is retained due to the capillary barrier. Since the TS layer is difficult to compact, it causes no restriction to root penetration. Conversely, fine textured overburden (OB) material can be highly compacted when used in reclamation areas due partly to the use of heavy machinery during substrate placement. This compaction makes root penetration into the OB layer difficult and mainly confines roots to the cover soil (Lazorko and Van Rees, 2012). The abrupt textural and bulk density transitions between the cover soil and OB substrate also create a capillary barrier, and thus more soil moisture can be held in the cover soil (Li et al., 2014; Jung et al., 2014). Therefore, substrate type may affect the development of understory plant communities in reclaimed forest ecosystems due to their influences on the soil moisture regime.

Another factor affecting understory plant community development is the overstory canopy. Overstory canopy cover affects light penetration through the overstory and thus the development of understory plant communities. Solar radiation reaching the understory decreases as canopy closure increases. As a result, soil surface evaporation decreases and water availability increases. But as canopy closure increases, leaf area and actual evapotranspiration also increases so there could also be a decline in water availability. The increase in shade can also trigger some plant species to increase growth which increases its own light capture and shades its smaller competitors (Semchenko et al., 2012; Schwinning and Weiner, 1998). Therefore, some plant species are outcompeted based on their slower growing rate and shade intolerance (Hautier et al., 2009; Lamb et al., 2009). Increasing overstory canopy closure also means that belowground tree biomass increases and thus competition for soil water and nutrients increases between the roots of understory and overstory plants.

Not all relationships between the overstory and understory are competitive as the herbaceous layer has been shown to benefit the overstory (Gillam, 2007). The biomass of the herbaceous layer in boreal forests is typically a small percentage of the total biomass (Gower et al., 2001) but its influence on nutrient cycling rates can be higher than its relative biomass would indicate. This layer can account for up to 16% of litter fall and this influences nutrient cycling greatly, relative to its small percentage of biomass (Gilliam, 2007). Greater abundance of understory shrub and herbaceous species biomass has been correlated with better tree height growth (Szwaluk and Strong, 2003). In addition, the herbaceous litter decomposes faster than overstory litter and thus again making the herbaceous layer an important component of the ecosystem in terms of its contribution to nutrient cycling (Muller, 2003).

Research about reclaimed understory plant communities in the AOSR have been limited to understory plant communities on recently reclaimed forest ecosystems (Brown and Naeth, 2014; Mackenzie and Naeth, 2010). There is little research examining understory plant communities in older forest ecosystems mainly because reclamation is a relatively new endeavor in the AOSR and there are not many old reclaimed forest ecosystems to examine. However, understanding the long-term trajectory of understory plant community development after reclamation is very important. This chapter will focus on understory plant communities that have developed over the 15 – 30 years since site reconstruction to characterize some of the older reclaimed forest ecosystems in the AOSR. These reclaimed forest ecosystems will have increased canopy cover and more aboveground biomass than younger ones and should offer best conditions for understory plant community development.

In this research I will test 3 hypotheses. First, understory plant communities established on a TS substrate will have greater cover and diversity than those established on an OB substrate, because the OB substrate will be compacted and will restrict the rooting zone to the PMM and thus understory vegetation development. Secondly, site characteristics such as water availability, soil carbon content and soil nutrients will influence understory plant communities. Plant communities developed on TS will have understory cover and foliar nutrient concentrations related to water availability because water availability is likely a most limiting factor due to coarse-textured TS freely draining water as it infiltrates. In OB plant communities, understory cover and foliar nutrient concentrations will not be related to water availability because the compaction of the OB substrate will limit water infiltration and keep soil water in the PMM layer. Last, understory plant community characteristics will be related to overstory tree growth. More specifically, understory foliar nutrient concentrations will be positively related to tree growth because roots from both overstory and understory species will have access to the same soil nutrient pool in the PMM and substrate. Since these research plots are in older reclaimed forest ecosystems, the trees are larger and demand more of the available nutrients and water in the cover soil. These nutrients stay in the structure of the trees for long periods of time thus reducing the pool of nutrients available to the understory plants and may have impact on understory foliar nutrient concentrations.

2.0 Materials and Methods

2.1 Site description

The research was conducted on Suncor Energy Inc. lease area 86/17, located in the AOSR, about 22 km north of Fort McMurray. A portion of this land has been reclaimed to forest ecosystems since 1976. In June 2011, six TS and six OB substrate plots were selected to represent a gradient of tree performance based on visual symptoms including stunted growth, foliar discolouration and needle dropping. At each plot, PMM placed over the substrate material, was used as a cover soil. The TS substrate plots had lodgepole pine (*Pinus contorta*) and the overburden (OB) substrate plots had white spruce (*Picea glauca*) planted during the growing season immediately following soil placement. In April 2012, 6 additional plots were added, including 3 TS and 3 OB plots, to increase the sample size. Plot size was 10 x 10 m and was used to perform the measurements described below.

Site history, including year of reclamation and tree planting and the amount of fertilizer applied was obtained from Suncor Energy Inc. reclamation site reports. Each plot was characterized with respect to aspect and slope using a compass and clinometer (Suunto, Finland), respectively. Two soil pits were dug on each plot to determine the thickness of the PMM cover soil applied and to sample for basic soil and root distribution properties. Bulk density in each soil pit was determined at 20 cm intervals from 0 to 100 cm using the steel ring method (Hillel, 1998). Soil strength was measured horizontally with a pocket soil penetrometer (CL-700, Soiltest Inc., USA) from 0 to 60 cm at 5 cm intervals. At each plot, soil samples collected from 5 random locations were composited and analyzed for soil organic carbon and soil inorganic nitrogen. Dissolved organic nitrogen (DON) and carbon (DOC) was extracted using a 2 mol L^{-1} KCl solution. Steam distillation was used to determine the concentrations of ammonium (NH_4^+) and nitrate (NO_3^-) in the KCl extracts. A portion of the KCl extracts was steam-distilled after adding MgO to determine NH_4^+ concentrations by a steam distillation system (Vapodest 20, C. Gerhardt, Königswinter, Germany). After adding Devarda's alloy, the extract was distilled again to determine NO_3^- concentrations. The NH_3 released during distillation was absorbed by 0.005 mol L^{-1} H_2SO_4 solutions, and the distillates were titrated with 0.01 mol L^{-1} NaOH using an automatic potentiometric titrator (719s Titrino, Metrohm, Herisau, Switzerland) to determine NH_4^+ and NO_3^- concentrations in the extracts. The DON concentration was calculated by subtracting NH_4^+ and NO_3^- concentrations from the total dissolved N concentration. Each air-dried soil sample was ground with a ball mill and used to analyze total carbon and N concentrations with a Carlo Erba NA 1500 elemental analyzer (Carlo Erba Instruments, Milano, Italy) at the Lethbridge Research Centre of Agriculture and Agri-Food Canada.

Soil water content and temperature were monitored on the 12 initial plots that were established in June 2011. The remaining plots were not monitored due to lack of equipment availability. One set of time domain reflectrometers (TDR) (CS616, Campbell Scientific, USA) and type T (copper-constantan) thermocouples (Omega Engineering, Montreal, Canada) were installed 10 cm below the PMM surface and 10 cm below the PMM / substrate interface, beginning in July 2011. Hourly means were recorded by CR10X data loggers (Campbell Scientific, USA).

2.2 Laboratory calibration of TDR probes and determination of soil moisture retention curve

Composite samples of PMM, peat, OB and TS were used to calibrate the TDR probes in the laboratory and to develop the soil moisture retention curve. A calibration curve was obtained by recording TDR readings in microseconds for six known water contents. The volumetric water contents at field capacity and permanent wilting point with matric potentials of 33 and 1500 kPa, respectively, were determined with a pressure plate. Three replicates of each soil material were initially saturated, weighed and then placed on a surface extraction plate where 5 and 10 kPa suctions were sequentially applied to the samples. Samples were then placed in pressure plate extractors with 50, 100, 500 and 1500 kPa pressure applied. Samples were weighed once water stopped leaving the sample at each pressure level. Following weighing, samples were placed back on the pressure plates and the next pressure was applied. Silt flour was added to the surface of the pressure plate to maximize contact between samples and the pressure plate. A line of best fit was plotted over the six measurements to form a moisture retention curve. With these calibrations, water availability was then calculated as the soil water content at field capacity minus that at the permanent wilting point. Mean plant available soil water content at the plots was calculated for July 1 to September 30 in 2011 and May 1 to September 30 in 2012. Plant available soil water data from one TS plot (plot TS3) was not included in the analysis due to a suspected faulty TDR probe which had water content much lower than the rest of the plots (Table A-1 of Appendix A) and the water content measurements did not show any fluctuation following precipitation events like the other TDRs that were installed at similar depths.

2.3 Understory plant community sampling

Five 1 x 1 m quadrats were randomly placed within the plot where there was no disturbance (foot traffic). In August 2012, plant species were identified and their total cover and modal height were estimated in each quadrat. Modal height was estimated by measuring the most common height for each species found in the quadrant. Also, shrub, herb, grass and moss / lichen understory layers were examined for their total cover and modal height. Total cover was visually estimated by the author only, to maintain consistency.

Species richness was calculated as the total number of species in a quadrat. Species diversity was calculated using the Shannon-Wiener Index (Shannon and Wiener, 1963). The Shannon-Wiener Index formula is:

$$H' = -\sum_{i=1}^{S} (p_i)(lnp_i)$$

where H' is the measure of species diversity, S is the number of species, p_i is the proportion of individuals in the total sample belonging to the *i*th species, and ln p_i is the natural logarithm of p_i. This index takes into account both species richness and their relative abundance. It is based on information theory as it measures the degree of uncertainty; if diversity is low, there is low uncertainty in predicting a particular species at random; likewise, if diversity is high, then there is high uncertainty in predicting a species that is selected at random (Smith and Smith, 2003). To measure species evenness, E_{var} (Smith and Wilson, 1996) was calculated:

$$E_{var} = 1 - 2/\pi \arctan \left\{ \sum_{S=1}^{S} \left(\ln(x_s) - \sum_{t=1}^{S} (x_t)/S \right)^2 /S \right\}$$

where S is the number of species in the sample and x_s is the abundance of the *s*th species. The output range is 0 – 1 with 0 representing minimum evenness and 1 representing maximum evenness. Species occurrence was calculated as the percent of quadrats a species occurred.

2.4 Nutrient concentrations in understory vegetation

Foliar samples of the two most common plant species were collected from each plot. In August 2011, foliar samples of *Melilotus* spp. (sweet clover) and *Epilobium angustifolium* (fireweed) on TS plots and on OB plots sweet clover and *Taraxacum officinale* (dandelion) were collected. In August 2012, foliar samples of dandelion and fireweed were collected on all TS and OB plots, including the new plots established in 2012. Sweet clover was not collected in 2012 because it is a nitrogen (N) fixing plant that may not reflect soil nutrient status. Fresh samples were promptly placed in coolers and transported to the lab for sample preparation and analysis. Samples were twice rinsed with distilled water and then oven-dried at 70 ˚C for 24 hours. Samples were then ground according to the method described by Kalra and Maynard (1991) and foliar nutrient analysis was conducted on those samples as described below.

Foliar samples were analyzed for organic N and organic C concentrations using a CN analyzer (NA Series 2, CE Instruments, Italy) at the Biogeochemical Analytical Service Laboratory, Department of Biological Sciences, University of Alberta. For analysis of potassium, phosphorus, magnesium and calcium, ground foliar samples were digested using nitric acid. Prepared samples were sent to the Canadian Centre for Isotopic Microanalysis, Department of

Earth and Atmospheric Sciences, University of Alberta and analyzed using an inductively coupled plasma (ICP) mass spectroscopy (PerkinElmer Optima 3000-DV, PerkinElmer Inc., Shelton, CT).

2.5 Tree measurements

Within each plot, tree height and diameter at breast height (DBH), at 1.3 m from the ground were measured following research plot establishment in June 2011 and in October 2012 for the plots established in 2011. Trees in the six additional plots established in spring 2012 were measured in April and October 2012. A standard diameter measuring tape was used for measuring DBH. In October 2012, the height increment in the last 5 years was measured by determining the stem length of the 5 most recent annual whorls on each tree. A 5 m height pole was used to measure tree height and a Vertex III hypsometer (Haglöf, Sweden) was used on two plots where trees were taller than 5 m. Tree height and DBH from each plot were then entered into allometric equations from Lambert et al. (2005) to calculate total aboveground biomass (organic dry mass per unit area). Aboveground biomass for each plot is the sum of all measured trees within the plot. The difference between the two sets of height, DBH and aboveground biomass measurements is the growth increment over the study period. Leaf area index (LAI) was measured in July 2012 with a plant canopy analyzer (LAI 2000, LI-COR Inc., USA). These measurements were taken on overcast days at 30 cm above the ground surface at each plot on a 3 x 3 grid (9 in total) with a matching open sky reading. Measurements were taken in the morning with the sensor facing west and in the afternoon facing east to avoid the sensor pointing towards the sun. An 180˚ view restrictor was placed on the sensor to reduce interference from the operator and direct sunlight.

2.6 Statistical Analysis

The Wilcoxon-Mann-Whitney non-parametric t-test was used to compare understory plant communities on TS and OB substrates because the Shapiro-Wilk procedure revealed that the understory plant community data were not normally distributed. Two-tailed t-tests were used to explore differences in site characteristics on TS and OB plots. Linear regression analyses were used to explore relationships between foliar nutrient concentrations and plant community/site characteristics including soil organic carbon, PMM depth, LAI and tree growth. Each variable met the assumption of a normal distribution. An α value of 0.05 was chosen to indicate statistical significance of t-test and linear regression analysis. Statistical analyses were performed using SAS software (SAS 9.2, SAS Institute Inc., Cary, NC).

Non-parametric multidimensional scaling ordination (NMS; Kruskal, 1964; Mather, 1976; McCune and Mefford, 2006) was used to visualize the differences in understory plant communities between TS and OB substrate. Procedures and analysis followed McCune et al. (2002) and the NMS ordination was performed using PC-ORD version 5.10 (MjM Software Design, Corvallis, OR). NMS was used with the quantitative version of the Sorenson distance measure. The dimensionality of the data set was first determined by plotting a measure of it ("stress") to the number of dimensions. A three-dimensional solution was requested of NMS because additional dimensions provided only slight improvement in fit. There were 250 runs with real data and eighty eight iterations were used for each NMS run with random starting configurations.

3.0 Results

3.1 Understory plant communities on tailings sand and overburden substrates

On TS plots, prickly rose (*Rosa acicularis*) and raspberry (*Rubus idaes*) had the highest cover and occurrence in the shrub layer; sweet clover (*Melilotus* spp.) and dandelion (*Taraxacum officinale*) had the highest cover and occurrence in the herbaceous layer (Table 2-1). In the grass layer, slender wheatgrass (*Agropyron trachycaulum*) and bluejoint grass (*Calamagrostis canadensis*) had the highest cover and occurrence; and in the moss layer purple horn toothed moss (*Ceratodon purpureus*) and golden ragged moss (*Brachythecium salebrosum*) had the highest cover and occurrence (Table 2-1). In the lichen layer, frog pelt (*Peltigera neopolydactyla*) and ribbed cladonia (*Cladonia cariosa*) had the highest cover and occurrence (Table 2-1).

On OB plots, willow (*Salix* spp.) and green alder (*Alnus crispa*) had the highest cover and willow and prickly rose had the highest occurrence in the shrub layer (Table 2-2). Sweet clover and dandelion had the most cover and highest occurrence in the herbaceous layer. In the grass layer, bluejoint grass and fowl bluegrass (*Poa palustris*) had the most cover and bluejoint grass and slender wheat grass had the highest occurrence. The moss layer is dominated by golden ragged moss and purple horn toothed moss; and the two most common lichen species, in cover and occurrence, were dog pelt (*Peltigera canina*) and frog pelt (Table 2-2). Understory foliar nutrient concentrations from 2011 and 2012 are presented in Table A-4 and Table A-5, respectively, in Appendix A).

The Shapiro-Wilk test for normality revealed that understory plant community layer cover had non-normal distributions (Table 2-3). Therefore the use of a non-parametric test was appropriate for comparing understory layer cover between OB and TS plots. The Wilcoxon-

Mann-Whitney test revealed that the understory total cover was significantly greater in TS than in OB plots ($p = 0.001$) (Table 2-4; Figure 2-1). More specifically, mean shrub layer cover was greater ($p = 0.003$) in the TS plots (8%) than in the OB plots (4%) (Table 2-4; Figure 2-1). The mean grass layer cover was significantly different ($p < 0.001$) between TS (20%) and OB plots (4%) (Table 2-4; Figure 2-1). Mean herbaceous layer cover was not significantly different ($p = 0.396$) between the TS (16%) and OB plots (11%) (Table 2-4; Figure 2-1). Mean cover for each plot are presented in Table A-2 of Appendix A.

T-tests on site characteristics between TS and OB plots showed some significant differences between the two substrates (Table 2-5). Tailings sand plots had more inorganic N and NO_3^- in the PMM layer than OB plots (Table 2-5). Also, according to Suncor Energy Inc. reclamation site reports, TS plots received more N fertilizer than the OB plots during the early years of reclamation on these plots (Table 2-5). Tree aboveground biomass increment (ABI) was also greater on TS plots (Table 2-5). Dandelion foliar magnesium concentration was greater on TS plots, however foliar potassium concentration was greater on OB plots (Table 2-5). Fireweed foliar potassium and phosphorus concentrations were greater on OB plots (Table 2-5). Foliar N concentrations in either understory species were not significantly different.

The stress and instability for the final NMS solution was 7.98 and <0.00001, respectively (Figure 2-2). The proportion of variance represented by axis 1, 2 and 3 is 0.27, 0.26 and 0.34, respectively, for a cumulative proportion of variance of 0.87. The final solution for the NMS ordination (Figure 2-2) shows that the understory plant communities and environmental variables on OB plots are closer together on axes 1 and 2 and the TS plots are more spread apart on axes 2 and 3. This result implies that substrate type influenced the plant community characteristics. Axis 2 corresponds to a PMM soil inorganic N gradient (greater amounts to the left, predominately representing TS plots, and less amounts to the right, predominately representing OB plots). Axis 3 corresponds to an overstory biomass gradient (plots with greater biomass towards the top) and a PMM soil strength gradient (more compacted plots towards the bottom). Axis 1 did not correspond to any environmental variable that show differences between TS and OB plots. It is important to note that there were no significant differences between the two substrates regarding species richness, evenness and diversity (Shannon-Weiner index) (Figure 2-3 and Table A-3 of Appendix A) and thus more weight should be given to the environmental variables in the NMS ordination results.

3.2 Plant community and site characteristics

On TS plots, total understory layer cover and grass layer cover were negatively related to PMM plant available soil water content in 2011 (r = -0.78, p = 0.046 and r = -0.80, p = 0.042, respectively) (Table 2-6). Grass layer cover was also positively related to soil NH_4 (r = 0.46, p = 0.046) (Table 2-6). Plot slope was positively related to total understory layer cover (r = 0.50, p = 0.034) and grass layer cover (r = 0.77, p = 0.002) (Table 2-6). Shrub layer and herbaceous layer were not related to site characteristics such as PMM plant available water content, soil inorganic N, and slope. None of the understory layers were related to PMM thickness, soil carbon content, bulk density or stand age.

Foliar potassium in dandelion and fireweed were positively related to plant available soil water content in 2012 (r = 0.93, p = 0.035 and r = 0.99, p = 0.030, respectively), but not in 2011 (Table 2-7). Foliar N in fireweed was positively related to soil NH_4 in 2012 (r = 0.74, p = 0.027), but not in 2011 (Table 2-7).

On OB substrate plots, total understory layer cover and shrub layer cover were positively related to PMM soil carbon content (r = 0.60, p = 0.024 and r = 0.93, p = 0.001, respectively)

(Table 2-6). Shrub layer cover was related to total PMM soil carbon content (r = 0.54, p = 0.037) (Table 2-6). Total understory layer cover and shrub layer cover were positively related to PMM total soil N content as well (r = 0.64, p = 0.017 and r = 0.93, p = 0.001, respectively) (Table 2-6). Understory layer covers were not related to PMM thickness, bulk density, slope or stand age.

On OB substrate plots, sweet clover foliar N and potassium were positively related to plant available soil water content (r = 0.87, p = 0.021 and r = 0.88, p = 0.005, respectively) and foliar calcium was negatively related to plant available soil water content (r = -0.88, p = 0.006) in 2011 (Table 2-7). No significant relationships between foliar macronutrients and plant available soil water were found in 2012. Foliar N in sweet clover was negatively related to soil N and carbon (r = -0.87, p = 0.021 and r = -0.84, p = 0.024, respectively) in 2011 (Table 2-7). Foliar phosphorus in sweet clover was also negatively related to soil N and carbon (r = -0.69, p = 0.040 and r = -0.85, p = 0.009, respectively) in 2011 (Table 2-7).

3.3 Plant community and tree productivity relationships

On TS plots, dandelion foliar magnesium was negatively related to stand age in 2011 (r = -0.87, p = 0.006), but not in 2012 (Table 2-8). Dandelion foliar phosphorus and potassium in 2012 were positively related to stand age (r = 0.83, p = 0.004 and r = 0.60, p = 0.040, respectively) (Table 2-8). In 2011, sweet clover foliar calcium was negatively related to overstory leaf area index, total aboveground biomass, aboveground biomass increment and 5-year height growth (r = -0.94, p = 0.001; r = -0.78, p = 0.020; r = 0.81, p = 0.014 and r = 0.84, p = 0.010, respectively) (Table 2-8), indicating that when there was more overstory, there was less uptake by the understory plants.

On OB plots in 2011, sweet clover foliar N was negatively related to stand age (r = 0.-90, p = 0.014) and foliar calcium was positively related to stand age (r = 0.85, p = 0.009) (Table 2-

8). Also in 2011, sweet clover foliar phosphorus was negatively related to overstory LAI and total aboveground biomass (r = -0.66, p = 0.047 and r = -0.78, p = 0.022, respectively) (Table 2-8). In 2011, overstory biomass increment was positively related to fireweed foliar N and phosphorus (r = 0.68, p = 0.042 and r = 0.81, p = 0.015, respectively) and overstory 5-year height increment was positively related to fireweed foliar phosphorus and potassium concentrations (r = 0.78, p = 0.046 and r = 0.76, p = 0.053) (Table 2-8), indicating that plots with greater understory foliar concentrations were related to greater overstory aboveground biomass production and tree growth.

4.0 Discussion

4.1 Effects of substrate type on understory plant communities

Understory species composition varied between TS and OB substrates (Table 2-1 and Table 2-2) and was related to water availability in the TS plots (Table 2-6) . Water availability has been show to affect understory plant community growth and composition (Bridge and Johnson, 2000; Hokkanen, 2006) and in my study the TS plots had greater water availability in the PMM layer than the OB plots (Table A-1 of Appendix A). Plants, depending on the species, have different water requirements and they will only grow within a range of plant available water content that meets their requirements. I observed in the field that plant roots penetrated into TS, but few penetrated into OB substrates and only 1.3 to 2.2% of total root length was observed in the OB substrate in a study conducted by Lazorko and Van Rees (2012). Therefore plants on TS plots likely had access to a greater volume of soil in their search for soil water and nutrients, which can lead to more tree growth and understory cover (Jung et al., 2014; Finér et al., 2007).

Overburden as a substrate had a different effect on the site's soil moisture regime and therefore the cover and composition of understory plant communities. Overburden is a fine textured material and it is easily compacted by heavy machinery during placement. It has mostly micropores which have low water infiltration rates (Carey, 2008) and less root penetration (Lazorko and Van Rees, 2012) from the PMM layer. Lack of water infiltration into the OB layer could increase water availability in the PMM, but my results did not support this as water availability in the PMM was not different between the OB and TS plots. Perhaps there was increased runoff above the OB because it has been shown that water can pond above the textural interface (Hardie et al., 2012), especially on steeper sloped plots.

Soil inorganic N in the PMM layer was greater in TS than in OB plots (Table 2-5; Figure 2-2) and this may explain why understory cover was greater on TS plots. More N was originally applied on the TS plots as well (Table 2-5) although that was more than 10 years ago and may have little effect on available N today (Miller, 1981). Aboveground biomass increment was also greater on TS plots (Table 2-5). However, TS and OB plots were planted with lodgepole pine and white spruce, respectively, as the dominant tree species and the differences in biomass were affected not only by site differences but also species differences. For instance, lodgepole pine has a tap root system that goes deeper into the soil profile whereas white spruce has a more lateral root system. Therefore, the first hypothesis that plant community cover would be greater on TS plots than on OB plots is accepted.

One limitation to this interpretation of the understory plant communities is that according to Suncor Energy Inc.'s site reclamation reports some understory species, including willow, dogwood, wild rose and raspberry, were planted in some reclamation areas and thus, the planting may have affected results in this study. However, since there is no way of knowing whether any of the plots were actually planted with understory species, I cannot claim they were planted.

4.2 Plant community relationships with site characteristics

On TS plots with greater understory layer cover there was less plant available soil water in 2011 (Table 6), a drier than usual year. The 2012 growing season had a similar trend, but the effect was not statistically significant (Table 2-6). Herbaceous layer cover was negatively related to plant available soil water in PMM on the OB plots (Table 2-6) indicating that the plots with greater understory cover likely had higher transpiration rates and tree roots were outcompeting understory species for available water. Naeth et al. (2011) found that even though plant available soil water contents in the spring were similar among plots with high and low vegetation cover, they decreased faster in high cover plots during the summer, indicating greater water loss from more transpiration. The reason for significant results in the dry year and not in the wet year may be due to higher evapotranspiration rates in the dry year creating a greater effect. On a boreal forest site, Lundbald and Lindroth (2002) found that transpiration in a dry growing season accounted for 78% of total evapotranspiration whereas transpiration only accounted for 52% in a wet one. This result indicates that in 2011, when there was significantly less water availability on higher cover sites, it may have been due to the drier year having a larger effect of transpiration rates.

Peat-mineral mix thickness and organic carbon content may have a strong influence on the site's soil moisture regime and thus on understory plant community cover. In this study I only found a strong relationship between understory plant community cover and soil organic carbon content, but not PMM thickness (Table 2-6). MacKenzie and Naeth (2010) and Purdy and MacDonald (2007) also reported that the thickness of the PMM layer did not affect plant community cover and composition. However, the reclaimed soils they investigated had a mineral subsoil between the PMM and substrate. The subsoil in their study had a finer texture than TS and thus a higher water holding capacity. My reconstructed soils did not have a subsoil layer and therefore I thought the effect of the TS would be greater; however, this was not the case. Burgers (2005) did find that poor vegetation was related to lower soil organic carbon content and my results indicated the same relationship on OB plots. Therefore, I accept my second hypothesis that on OB substrates, PMM soil carbon and nutrients may be limiting understory plant community development and that water availability is not likely the most limiting factor to growth in the understory. However some understory foliar nutrients were related to water availability suggesting that plants are less limited by water have greater nutrient uptake. See section 4.3 for discussion on root nutrient uptake.

On TS plots, understory species richness decreased with the age of the site (r = 0.73, p = 0.02), indicating that as the trees get older and larger, the tree canopy expands and intercepts more light. As a result, less light reaches the understory layer, mortality of shade intolerant species increases and thus species richness decreases. My results are consistent with Jules et al. (2008) who found that understory species richness was the highest in young stands and then gradually decreased until reaching stand age of 55 before understory species richness began to increase again.

4.3 Plant community relationships with tree productivity

Nitrogen is stored in soils mostly in the organic N form, which is closely associated with the amount of organic carbon fixed by plants. The total N found in soils is thus correlated with total organic C that indicates past C fixation by the plant. Plant analyses are based on the relationship between nutrients in a plant and nutrient availability in the soil. The relationships between understory foliar N and phosphorus concentrations and tree ABI (Table 2-7) indicate that plots richer in these nutrients, as indicated by understory species having higher nutrient concentrations, had trees that grew at a faster rate than plots where there were less nutrients. Also, understory plants have annual litter fall which decomposes rather quickly and contributes organic matter and buildup of nutrients in the soil that will become available for plant uptake again (Nilsson and Wardle, 2005) which will further contribute to improved tree growth. Nutrients are transported to roots by mass transport and diffusion through the soil solution. Therefore, the soil moisture regime is important as mass flow only occurs when soils have high water content. Diffusion is far more efficient in water filled pores than along tortuous routes in water films on the surfaces of soil particles (Havelin et al., 2005). So in a drier year, such as in 2011, diffusion of nutrients is less efficient and thus there would be less root nutrient uptake. Therefore, I accept my third hypothesis that understory plant communities are influenced by the overstory tree cover and growth characteristics.

5.0 Conclusions

Land reclamation following surface mining involves the use of substrate materials such as TS and OB to reconstruct the landscape. The properties of these substrates affect the understory plant communities growing on the cover soil above. TS substrates tended to have more total, shrub and grass layer cover. The thickness of the PMM layer may not directly influence understory plant community cover, but PMM properties such as inorganic N content indicated that TS plots were richer and thus explained greater understory plant community cover. Decision makers and reclamation land managers should consider the effects of substrates and peat-mineral mix on the understory plant communities while reclaiming surface mines in the AOSR.

Table 2-1 Understory species composition on tailings sand substrate plots in the Athabasca oil sands region.

Layer	Latin name (common name)	Cover (%)	Occurrence (%)	Modal height (cm)
Shrub	*Rosa acicularis* (prickly rose)	3.96	22	29
	Rubus idaeus (raspberry)	1.38	13	30
	Salix spp. (willow)	1.13	9	65
	Caragana aborescens (Siberian peashrub)	1.04	7	52
	Shepherdia canadensis (soopalalie)	0.44	2	20
	Symphoricarpos albus (common snowberry)	0.07	4	48
Herbaceous	*Melilotus* spp. (sweet clover)	7.74	69	36
	Taraxacum officinale (dandelion)	5.23	53	13
	Aster ciliolatus (Lindley's aster)	1.00	18	15
	Fragaria virginiana (wild strawberry)	1.00	11	8
	Erysimum cheiranthoides (wormseed mustard)	0.22	9	33
	Achillea millefolium (common yarrow)	0.20	9	13
	Epilobium angustifolium (fireweed)	0.16	9	27
	Galium boreale (northern bedstraw)	0.16	4	35
	Hieracium spp. (hawkweed)	0.09	4	28
	Vicia americana (wild vetch)	0.09	4	20
	Chenopodium album (Lamb's-quarters)	0.02	2	5
Grass	*Agropyron trachycaulum* (slender wheat grass)	15.29	62	31
	Calamagrostis canadensis (bluejoint)	2.09	36	52
	Poa pratensis (Kentucky bluegrass)	0.27	7	28
	Poa palustris (fowl bluegrass)	0.13	9	48
	Sedge spp. (sedge)	0.13	7	37
	Bromus inermis ssp. Pumpellianus (northern brome)	0.04	11	56
Moss	*Ceratodon purpureus* (purple horn toothed)	6.00	47	N/A[1]
	Brachythecium salebrosum (golden ragged)	1.30	11	N/A
	Polytrichum juniperinum (juniper haircap)	1.30	9	N/A
	Eurhynchium pulchellum (common beaked)	0.09	4	N/A
Lichen	*Peltigera neopolydactyla* (frog pelt)	0.14	11	N/A
	Cladonia cariosa (ribbed cladonia)	0.09	9	N/A
	Cladonia coniocraea (tiny toothpick cladonia)	0.05	4	N/A
	Peltigera canina (dog pelt)	0.05	4	N/A

[1]N/A: Not applicable because height was not measured for mosses and lichens

Table 2-2 Understory species composition on overburden substrate plots in the Athabasca oil sands region**.**

Layer	Name (common name)	Cover (%)	Occurrence (%)	Modal height (cm)
Shrub	*Salix* spp. (willow)	3.07	16	112
	Alnus crispa (green alder)	2.04	4	15
	Ribes oxyacanthoides (northern gooseberry)	0.56	2	50
	Rosa acicularis (prickly rose)	0.26	9	14
	Cornus stolonifer (red osier dogwood)	0.04	2	20
	Ribes lacustre (black gooseberry)	0.04	2	10
	Shepherdia Canadensis (soopalalie)	0.02	2	10
Herbaceous	*Melilotus* spp. (sweet clover)	3.22	73	19
	Taraxacum officinale (dandelion)	2.59	76	9
	Epilobium angustifolium (fireweed)	2.38	60	20
	Fragaria virginiana (wild strawberry)	2.07	38	8
	Aster ciliolatus (Lindley's aster)	0.31	16	8
	Trifolium hybridum (alsike clover)	0.20	11	8
	Sonchus uliginosus (smooth perennial sow thistle)	0.07	4	13
	Hieracium spp. (hawkweed)	0.04	4	5
	Achillea millefolium (common yarrow)	0.02	2	5
Grass	*Calamagrostis canadensis* (bluejoint)	2.04	16	22
	Poa palustris (fowl bluegrass)	1.47	7	30
	Agropyron trachycaulum (slender wheat grass)	0.62	11	23
Moss	*Brachythecium salebrosum* (golden ragged)	23.87	67	N/A
	Ceratodon purpureus (purple horn toothed)	20.82	82	N/A
	Hylocomium splendens (stair-step)	0.89	2	N/A
	Ptilium crista-castrensis (knight's plume)	0.04	2	N/A
Lichen	*Peltigera canina* (dog pelt)	0.42	18	N/A
	Peltigera neopolydactyla (frog pelt)	0.13	13	N/A
	Usnea hirta (shaggy old man's beard)	0.13	2	N/A
	Physcia adscendens (hooded rosette)	0.09	9	N/A
	Cladonia coniocraea (tiny toothpick cladonia)	0.07	7	N/A
	Cladonia sulphurina (sulphur cup)	0.04	4	N/A
	Cladonia cariosa (ribbed cladonia)	0.02	2	N/A
	Cladonia cenotea (powdered funnel cladonia)	0.02	2	N/A

[1]N/A: Not applicable because height was not measured for mosses and lichens

Table 2-3 Shapiro-Wilk test for normality for understory plant community layer cover on tailings sand and overburden substrate plots in the Athabasca oil sands region.

Layer	Tailings sand		Overburden	
	Shapiro-Wilk statistic	P value	Shapiro-Wilk statistic	P value
Shrub	0.614	<0.001	0.375	<0.001
Herbaceous	0.839	<0.001	0.924	0.0058
Grass	0.774	<0.001	0.409	<0.001
Total cover	0.914	0.026	0.835	<0.001

Table 2-4 Wilcoxon-Mann-Whitney non-parametric t-test comparing understory plant community layer cover on tailings sand and overburden substrates plots in the Athabasca oil sands region.

Understory layer	Plot type[1]	N	Sum of scores	Expected under H0	Standard deviation under H0	Mean Score	Z – Normal approximation	Two-sided Pr > |Z|
Shrub	TS	45	2372.0	2047.5	107.9	52.7	3.011	0.003
	OB	45	1722.0	2047.5	107.9	38.3		
Herbaceous	TS	45	2153.0	2047.5	123.8	47.8	0.848	0.396
	OB	45	1942.0	2047.5	123.8	43.2		
Grass	TS	45	2729.0	2047.5	119.5	60.6	5.700	<0.001
	OB	45	1366.0	2047.5	119.5	30.4		
Total	TS	45	2536.5	2047.5	123.9	56.4	3.943	<0.001
	OB	45	1558.5	2047.5	123.9	34.6		

[1] TS and OB are tailings sand substrate and overburden substrate, respectively.

Table 2-5 T-tests comparing site characteristics on tailings sand and overburden plots in the Athabasca oil sands region.

Site characteristic	Site type[1]	Mean (standard error)	P value	Equality of variance
Inorganic nitrogen (mg kg^{-1}), PMM[2]	TS OB	13.1 (1.2) 9.5 (2.3)	0.02	equal
Nitrate nitrogen (mg kg^{-1}), PMM	TS OB	8.0 (0.7) 5.6 (0.7)	0.01	equal
Nitrogen fertilizer (kg ha^{-1} $year^{-1}$)	TS OB	391.5 (18.6) 242.7 (30.3)	<0.01	equal
ABI[3] (mg ha^{-1} $year^{-1}$)	TS OB	4.1 (0.4) 2.6 (0.6)	0.05	equal
Foliar Mg, dandelion (mg g^{-1})	TS OB	7.8 (0.6) 5.5 (0.3)	<0.01	equal
Foliar K, dandelion (mg g^{-1})	TS OB	43.0 (3.5) 59.7 (1.0)	<0.01	unequal
Foliar K, fireweed (mg g^{-1})	TS OB	13.1 (1.9) 20.5 (2.1)	0.03	equal
Foliar P, fireweed (mg g^{-1})	TS OB	2.7 (0.2) 4.4 (0.6)	0.02	unequal

[1] TS and OB are tailings sand substrate and overburden substrate, respectively.
[2]PMM is peat-mineral mix cover soil
[3] ABI is tree aboveground biomass increment.

Table 2-6 Coefficient of determination (R^2) and probability (p) for relationships between understory plant community layer cover and site characteristics on tailings sand and overburden substrate plots in the Athabasca oil sands region.

Dependent / independent variable	Tailings Sand				Overburden			
	2011		2012		2011		2012	
	R^2	p	R^2	p	R^2	p	R^2	p
Total understory layer cover								
Plant available soil water (%), PMM[1]	**-0.78**	**0.046**	0.61	0.120	0.18	0.471	0.16	0.510
Soil carbon content, PMM	0.02	0.956	0.02	0.956	**0.60**	**0.024**	**0.60**	**0.024**
Inorganic nitrogen content, PMM	0.30	0.126	0.30	0.126	**0.64**	**0.017**	**0.64**	**0.017**
Plot slope	**0.50**	**0.034**	**0.50**	**0.034**	0.46	0.066	0.46	0.066
Shrub layer cover								
Soil carbon content, PMM	-0.03	0.943	-0.03	0.943	**0.93**	**0.001**	**0.93**	**0.001**
Soil carbon content (Mg ha^{-1}), PMM	0.11	0.856	0.11	0.856	**0.54**	**0.037**	**0.54**	**0.037**
Soil nitrogen content, PMM	-0.11	0.856	-0.11	0.856	**0.93**	**0.001**	**0.93**	**0.001**
Herbaceous layer cover								
Plant available soil water (%), PMM	0.02	0.956	0.10	0.882	**0.94**	**0.001**	**0.85**	**0.027**
Grass layer cover								
Plant available soil water (%), PMM	**-0.80**	**0.042**	0.63	0.110	0.74	0.061	0.37	0.274
Plot slope	**0.77**	**0.002**	**0.77**	**0.002**				
Soil NH_4, PMM	**0.46**	**0.046**	**0.46**	**0.046**	0.23	0.233	0.23	0.223

[1] PMM is peat-mineral mix

Table 2-7 Coefficient of determination (R^2) and probability (p) for relationships between understory foliar nutrients and site characteristics on tailings sand and overburden substrate plots in the Athabasca oil sands region.

Dependent / independent variable	Tailings Sand				Overburden			
	2011		2012		2011		2012	
	R^2	p	R^2	p	R^2	p	R^2	p
Foliar potassium – fireweed								
Plant available soil water (%), PMM[1]	N/A[2]	N/A	**0.99**	**0.030**	0.47	0.132	0.46	0.136
Foliar nitrogen – fireweed								
Soil NH_4, PMM	N/A	N/A	**0.74**	**0.027**	0.01	0.991	-0.26	0.663
Foliar potassium – dandelion								
Plant available soil water (%), PMM	0.19	0.65	**0.0.93**	**0.035**	N/A	N/A	0.43	0.158
Foliar nitrogen – sweet clover								
Plant available soil water (%), PMM	-0.11	0.856	N/A	N/A	**0.87**	**0.021**	N/A	N/A
Soil nitrogen, PMM	0.05	0.904	N/A	N/A	**-0.87**	**0.021**	N/A	N/A
Soil carbon, PMM	0.13	0.823	N/A	N/A	**-0.84**	**0.029**	N/A	N/A
Foliar potassium – sweet clover								
Plant available soil water (%), PMM	-0.10	0.889	N/A	N/A	**0.88**	**0.005**	N/A	N/A
Foliar calcium – sweet clover								
Plant available soil water (%), PMM	**0.86**	**0.023**	N/A	N/A	**-0.88**	**0.006**	N/A	N/A
Foliar phosphorus – sweet clover								
Soil nitrogen, PMM	0.07	0.864	N/A	N/A	**-0.69**	**0.040**	N/A	N/A
Soil carbon, PMM	0.01	0.991	N/A	N/A	**-0.85**	**0.009**	N/A	N/A

[1] PMM is peat-mineral mix.
[2]N/A is not available because samples of fireweed on tailings sand plots were not collected in 2011 and samples of sweet clover we not collected in 2012.

Table 2-8 Coefficient of determination (R^2)and probability (p) for relationships between understory plant community and overstory tree growth characteristics on tailings sand and overburden substrate plots in the Athabasca oil sands region.

Dependent / independent variable	Tailings sand				Overburden			
	2011		2012		2011		2012	
	R^2	p	R^2	p	R^2	p	R^2	p
Foliar magnesium – dandelion								
Stand age	**-0.87**	**0.006**	-0.03	0.896	N/A	N/A	-0.16	0.798
Foliar phosphorus – dandelion								
Stand age	0.37	0.261	**0.83**	**0.004**	N/A	N/A	0.20	0.754
Foliar potassium – dandelion								
Stand age	0.04	0.863	**0.60**	**0.040**	N/A	N/A	-0.18	0.778
Foliar calcium – sweet clover								
Leaf area index	**-0.94**	**0.001**	N/A	N/A	0.45	0.204	N/A	N/A
Total biomass	**-0.78**	**0.020**	N/A	N/A	0.49	0.193	N/A	N/A
Biomass increment	**-0.81**	**0.014**	N/A	N/A	-0.20	0.754	N/A	N/A
5-year height increment	**-0.84**	**0.010**	N/A	N/A	-0.48	0.198	N/A	N/A
Stand age	0.01	0.991	N/A	N/A	**0.85**	**0.009**	N/A	N/A
Foliar nitrogen – sweet clover								
Stand age	0.62	0.063	N/A	N/A	**-0.90**	**0.014**	N/A	N/A
Foliar phosphorus – sweet clover								
Biomass increment	-0.38	0.253	N/A	N/A	**-0.66**	**0.047**	N/A	N/A
Total biomass	-0.49	0.192	N/A	N/A	**-0.78**	**0.022**	N/A	N/A
Foliar nitrogen – fireweed								
Biomass increment	0.11	0.854	0.01	0.990	**0.68**	**0.042**	-0.07	0.875
Foliar phosphorus – fireweed								
Biomass increment	0.15	0.802	0.01	0.990	**0.81**	**0.015**	0.11	0.854
5-year height increment	-0.01	0.992	0.08	0.862	**0.78**	**0.046**	0.02	0.987
Foliar potassium – fireweed								
5-year height increment	0.46	0.199	0.08	0.860	**0.76**	**0.053**	-0.01	0.991

N/A is not applicable because some variables were not measured in both years of the study.

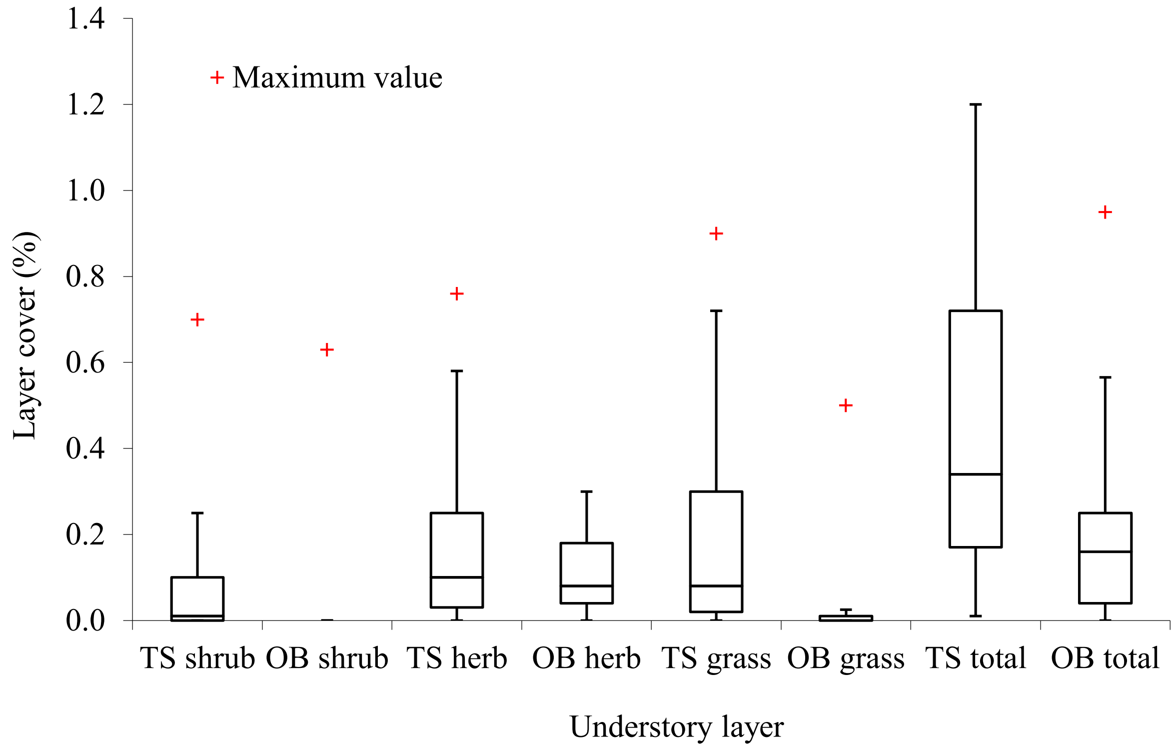


Figure 2-1 Box plots of understory plant community layer cover on tailings sand (TS) and overburden (OB) substrate plots in the Athabasca oil sands region. The boxplot displays the inner fence (1.5 x inner quartile range), first quartile, median, third quartile, inner fence and the maximum value (+). Minimum value was zero for all layers. The rectangle spans the first quartile to the third quartile.

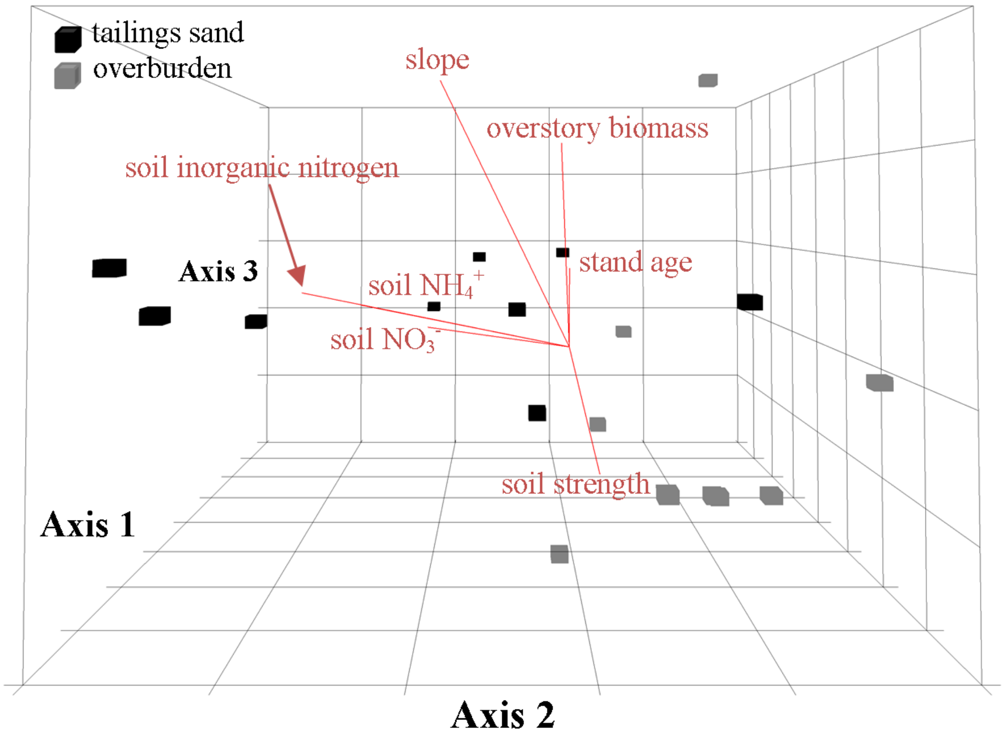


Figure 2-2 Non-metric multi-dimensional scaling ordination of understory plant communities and environmental variables on Suncor Energy Inc. lease 86/17. The proportion of variance represented by axes 1, 2 and 3 are 0.27, 0.26 and 0.34, respectively. Environmental variables with r^2 >0.2 are represented as radiating lines from the centroid of the ordination scores. The tighter grouping of overburden plots indicate they have more similar properties between their plots than the tailings sand plots.

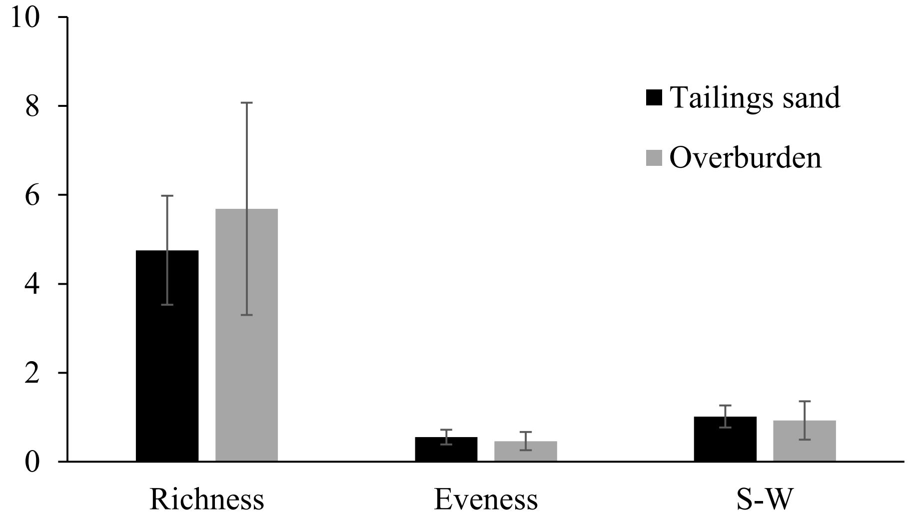


Figure 2-3 Plant community comparison of richness, evenness and Shannon-Wiener index between tailings sand and overburden substrate plots in the Athabasca oil sands region. Error bars represent the standard errors of the mean.

3. Chapter 3 Water availability limited the growth of lodgepole pine on tailings sand but not white spruce on overburden substrates in reclaimed forest ecosystems in the Athabasca oil sands region

1.0 Introduction

Water uptake by tree roots is more difficult when there is low water availability because water is held by soil particles at higher matric attraction (lower matric water potential), making it harder to be extracted by the roots. Additionally, trees growing in soils with low water holding capacity can be further stressed because less water is held in the solum to begin with. Furthermore, low water availability can negatively affect tree growth and in severe cases can even cause tree mortality (Davies and Zhang, 1991; Bréda et al., 2006). Tree growth is negatively affected under water stress because trees will close stomata on their leaf surfaces to regulate water flow, which reduces CO_2 uptake and ultimately slows tree growth. This water potential gradient in the soil-plant-atmosphere continuum, from the soil-root interface to the leaves, controls water flow. Two factors that cause water potential to decrease in the soil-plant-atmosphere continuum are: increasing potential evapotranspiration and drying soil (lowering water availability) (Bréda et al., 2006). Additionally, climate change is expected to increase the frequency and severity of droughts (Saxe et al., 2001; Salinger, 2005) resulting in increased potential evapotranspiration and lower water availability. Since increasing potential evapotranspiration is partially a climate-related issue and water availability is mainly a soil condition that can be affected by water holding capacity, it is important for land reclamation practioners to consider water availability when reconstructing soils.

Surface mining in the Athabasca oil sands region (AOSR) is a disturbance at a landscape scale that includes the removal of vegetation, soil and overburden (OB) materials in order to gain access to the oil sands deposit. Following mining activities on leased provincial Crown land, oil sands companies are required by law to reclaim the disturbed land to equivalent land capability (Government of Alberta, 2003). Equivalent land capability can be interpreted broadly depending on the end land use (Powter et al., 2012) but essentially it requires land reclamation practioners to create self-sustaining ecosystems with productivity similar to or better than that existed before the disturbance in the AOSR. Commercial forestry is considered as one of the most common end land uses (CEMA, 2006) so establishing productive forest ecosystems is an important land reclamation goal in the AOSR.

Forest ecosystem productivity in the AOSR may be limited by water availability because the region is subject to moderate water deficits for short periods during the growing season (Natural Regions Committee, 2006; Bothe and Abraham, 1993). Average annual precipitation is 455 mm with 342.2 mm falling as rainfall (Environment Canada, 2013) and average annual actual evapotranspiration is 300 mm at Fort McMurray airport (Alberta Environment and Sustainable Resource Development, 2013). When evapotranspiration exceeds precipitation there is a water deficit. Some of the water deficit can be mitigated by water stored in the soil but as a result water availability is reduced over time due to the water deficit. Furthermore, future climate warming is expected to be the greatest in the boreal and subarctic regions (IPCC, 2007) which could increase the frequency and severity of water deficits if the amount of precipitation does not increase. Thus, forest ecosystem productivity in the AOSR may become increasingly limited by water availability.

Reconstructed soils are usually comprised of two layers: a substrate layer composed of tailings sand (TS) or OB, and a cover soil composed of either salvaged peat and mineral soils, known as peat-mineral soil mix (PMM) or salvaged LFH layer and mineral soils, known as LFH-mineral mix (Naeth et al., 2013; Rowland et al., 2009). The cover soil is the growth medium for vegetation. Coarse textured TS has low water holding capacity and rapid drainage (Mikula et al., 1996). In contrast, OB is fine textured and has high water holding capacity and imperfect to poor drainage. Both of these substrates have low organic matter content and are inadequate for plant growth. Also, the textural interface between PMM and the substrate layer affects the soil moisture regime and plant growth (Jung et al., 2014). Finer textured PMM overlying coarse textured TS creates a capillary barrier for water movement between the two layers (Naeth et al., 2011). Water held at stronger matric forces in smaller pores in the PMM will resist draining into the larger pores in the TS until water content is greater than field capacity (Porro, 2001). As a result, reconstructed soils in the AOSR that have TS as a substrate layer may be more susceptible to low water availability leading to reduced forest ecosystem productivity and therefore this issue requires further investigation. Unlike TS, OB has a high proportion of micropores because of its finer texture and can be potentially compacted by heavy machinery during soil reconstruction. Compaction reduces water infiltration into the substrate and in doing so increases water content above the textural interface.

Cover soil, on the other hand has different soil physical properties than TS and OB and largely affects vegetative performance in reclaimed forest ecosystems. For instance, Burgers (2005) found that lower soil organic carbon levels in PMM were related to poor vegetation cover in reclaimed forest ecosystems in the AOSR. This result is likely because organic matter (i.e., peat), in PMM, functions to increase water holding capacity (Moskal et al., 2001) and its decomposition is a primary source of nutrients for vegetation growing in reclaimed forest ecosystems (Hemstock et al., 2010).

Cover soil thickness is another factor affecting vegetative performance in reclaimed forest ecosystems in the AOSR although there are conflicting assessments of this factor in the literature. In theory, a thicker cover soil provides more soil volume for plant roots to extract water and nutrients from. Some research shows that thicker cover soils have greater understory native plant densities and cover (Purdy and MacDonald, 2007), whereas Mackenzie and Naeth (2010) found that even though cover soil thickness ranged from 10 cm to 20 cm, there was no difference in understory plant community cover.

Indicators for water stress are low water availability during the growing season (Davies and Zhang, 1991), shoot water potential in trees (Turner, 1981) and foliar $\delta^{13}C$ in trees (Farquhar et al., 1989). Water availability describes the water status of soils (Fisher and Binkley, 2000) and is the amount of water held in the soil between field capacity and permanent wilting point. Field capacity is the amount of water held by the soil matrix once gravitational drainage ceases and permanent wilting point is when the water in the soil is held at such a high tension that plant roots are unable to extract it from the soil. Obviously, the balance between precipitation and evapotranspiration largely influences water availability but soil properties such as soil texture and organic matter content affect soil water holding capacity (Hillel, 1998) and thus water availability. Soil organic matter increases field capacity more than permanent wilting point, and therefore high soil organic matter content results in more water availability in both natural and reconstructed soils (Hudson, 1994; Moskal et al., 2001). In reconstructed soils, soil organic matter can be added to increase water-holding capacity and improve soil quality in land reclamation (Larney and Angers, 2012).

Analysis of shoot water potential can be used to assess water stress experienced by trees. Evapotranspiration of water from leaves creates tension (shoot water potential) in leaves that pulls water towards the stomata from the xylem, the roots and finally the soil (Boyer, 1995). When evapotranspiration rates increase during the growing season, shoot water potential decreases (to become more negative) so roots can extract water from the soil, which then moves upwards via the xylem and out of the stomata of leaves as required for transpiration. As soil water potential approaches permanent wilting point, it becomes more difficult for roots to extract water from the soil because water is held in the soil at a lower matric potential leading to water stress.

Isotopic abundance of ^{13}C (measured as $\delta^{13}C$) in plant foliage can also indirectly indicate water stress (Farquhar et al., 1989). The carbon in CO_2 is comprised of two stable isotopes: ^{12}C and ^{13}C. Under normal, non-water stressed conditions in C_3 plants, heavier isotope (^{13}C) discrimination occurs during photosynthesis due to slower physical and chemical reactions during CO_2 diffusion and carboxylation by RuBisCO (Farquhar et al., 1989). However, when the plant is managing water stress, the stomata close and there is less discrimination against ^{13}C. Therefore, when foliar samples are analyzed for $\delta^{13}C$, less negative results may indicate that the plant experienced water stress during the growing season (Farquhar et al., 1989).

The objectives of this research were to characterize soil physical properties in the PMM, TS and OB layers and determine whether these properties were affecting tree-water relations and growth in reclaimed forest ecosystems in the AOSR. I will test 3 hypotheses. First, shallower PMM thickness and lower organic carbon content would have decreased water availability. Second, reclaimed forest ecosystems with lower growth rates were affected by lower water availability. Lastly, reclaimed forest ecosystems with lower growth rates exhibit greater water stress, as indicated by more negative shoot water potentials and greater foliar $\delta^{13}C$.

2.0 Materials and methods

Tailings sand plots were located on tailings pond dykes on Suncor Energy Inc. lease 86/17and were established and planted with lodgepole pine (*Pinus contorta*) between 1991 and 1996 (Table A-1 of Appendix A). They were in upper to mid slope positions with slopes ranging from 21 to 42% with various aspects. Overburden plots were located on overburden waste dumps on Suncor Energy Inc. lease 86/17 and were established and planted with white spruce (*Picea glauca*) between 1982 and 1994 (Table A-1 of Appendix A). Topographic positions ranged from crest to toe and slope ranged from 2 to 35%; plot aspect varied as well (Table A-1 of Appendix A). Please refer to Chapter 2 for more detailed plot descriptions, soil sampling methods and tree measurement methods.

Predawn shoot water potential was recorded once in late August 2011, and 3 times at four week intervals from June to August in 2012. Midday shoot water potential was also recorded 3 times at the same interval in 2012. At each interval, I collected a branch 10 to 15 cm long, from the upper one-third of 5 trees in each plot and shoot water potential was immediately measured using a pressure chamber (PMS Instruments, USA). Relative changes in shoot water potential from midday to predawn were calculated by subtracting predawn from midday shoot water potential.

Composite foliar samples were collected from three branches from the upper one-third of 5 randomly selected trees in each plot in October 2011 and 2012. Samples were rinsed three times with distilled water and oven-dried at 60˚C for 24 hours. Current year and one year old needles were separated and ground to a fine powder in a MM200 ball grinder (Retsch, USA). Concentrations of total carbon and ^{13}C abundance were determined with a stable isotope ratio mass spectrometer (Optima-EA, Micromass Ltd., Manchester, UK) linked to a Carlo Erba NA

1500 elemental analyzer (Carlo Erba Instruments, Milano, Italy). The isotope abundance was expressed as a relative deviation from international standards of Pee Dee Belemite (PDB) for ^{13}C.

A weather station located near Pond 1 on Suncor Energy Inc. lease 86/17 and maintained by O'Kane and Associates, collected average rainfall, air temperature, relative humidity, wind speed, wind direction, and net radiation. Air temperature and rainfall normals (1971-2000) at Fort McMurray airport were acquired from Environment Canada.

2.1 Statistical analysis

Linear regression analyses were performed to explore relationships between soil characteristics, tree measurements and/or water stress indicators. Each variable met the assumption of a normal distribution. An alpha value of 0.05 was chosen to indicate statistical significance of the linear regression analyses. SAS version 9.2 (SAS Institute Inc., Cary, NC) was used for linear regression analyses.

3.0 Results

3.1 Climate and site characteristics

The normal (1971 – 2000) growing season (May – September) precipitation and mean monthly temperature at Fort McMurray airport (Environment Canada, 2013) during the growing season was 312.5 mm and 13.3˚C, respectively. During the 2011 study period the condition in the growing season was drier than a normal year; the 2011 growing season had a total precipitation of 199 mm. The 2012 growing season precipitation was relatively normal at 306.5 mm. Both 2011 and 2012 had higher than normal mean monthly temperatures of 15.8 and 16.2 ˚C, respectively (Figure 3-1). Less precipitation contributed to harsher drought conditions in

2011 than in 2012 and higher than normal temperatures increased potential evapotranspiration in both years.

Site characteristics for each plot are presented in Table A-1 of Appendix A. For TS plots, PMM cover soil thickness ranged from 12 to 30.5 cm. Soil strength in the 0 to 10 cm PMM layer ranged from 0.6 to 2.0 kg m^{-2}. Bulk density ranged from 0.61 to 1.4 g cm^{-3} in the PMM layer and from 1.30 to 1.53 g cm^{-3} in the substrate. Soil organic carbon content ranged from 1.5 to 9.1% or from 25.4 to 196.6 Mg ha^{-1} in PMM. Mean volumetric plant available soil water content in PMM in the 2011 and 2012 growing seasons ranged from 0.10 to 0.15 and 0.10 to 0.22, respectively. Mean plant available water storage in the PMM in the 2011 and 2012 growing seasons ranged from 13 to 41 and 13 to 67 mm, respectively (Table A-1 of Appendix A).

Tree measurements for each plot are listed in Table A-6 of Appendix A. The mean tree height and DBH increments on TS plots during the study period ranged from 14 to 27 and 0.14 to 0.36 cm, respectively. Aboveground biomass increment ranged from 2.7 to 5.7 Mg ha^{-1} and five-year (2008 to 2012) tree height increment ranged from 0.76 to 184.5 m. Leaf area index in 2012 ranged from 0.62 to 3.23 m^2 m^{-2}. Tree density ranged from 2000 to 2700 stems ha^{-1} (Table A-6 of Appendix A).

On OB plots, the PMM cover soil thickness ranged broadly from 9.5 to 47.5 cm. Soil strength in the 0 to 10 cm depth in the PMM layer ranged from 0.5 to 1.9 kg m^{-2}. Bulk density ranged from 0.32 to 1.36 g cm^{-3} in the PMM layer and from 1.34 to 1.64 g cm^{-3} in the substrate. Soil organic carbon content in PMM ranged from 4.5 to 18.4% or from 58 to 490.7 Mg ha^{-1}. Mean volumetric plant available soil water content in the PMM ranged from 0.02 to 0.18 and 0.08 to 0.2 in 2011 and 2012, respectively. Mean plant available water storage in the PMM ranged from 5 to 36 mm and 7 to 46 mm in 2011 and 2012, respectively (Table A-1 of Appendix A).

Tree measurements for the OB plots are listed in Table A-6 of Appendix A. Plot mean tree height increment during the study period ranged from 11 to 41 cm; height increment could not be calculated for most trees on plots OB1 and OB6 because the hypsometer measurement rounded to the nearest 0.1 m and therefore the change in height was not able to be accurately captured. DBH increment ranged from 0.17 to 0.64 cm. Aboveground biomass increment ranged from 0.6 to 6.1 Mg ha^{-1} and five-year (2008 to 2012) tree height increment ranged from 0.70 to 2.02 m. Neither five-year height increment could not be accurately measured on plot OB6 by either of the height measurement methods used in this study (5 m height pole and Vertex III hypsometer) because the trees were too tall for the 5 m height pole (8.9 m mean tree height) and the dense canopy cover made it impossible to view the tree tops and whorls with the Vertex III hypsometer. Leaf area index in 2012 ranged from 1.04 to 4.62 m^2 m^{-2} and tree density ranged from 1900 to 3200 stems ha^{-1} (Table A-6 of Appendix A). Plot OB6 was removed from the analysis because its cover soil consists predominantly of peat, an organic soil (>17% organic carbon; Soil Classification Working Group, 1998), and therefore has different water retention properties from the PMM soils (Moskal et al., 2001).

3.2 Water availability and site characteristics and tree growth relationships

On TS plots five-year height increment was positively related to plant available water content in the PMM layer in 2011 and 2012 (r = 0.99, p = 0.001 and r = 0.78, p = 0.019, respectively) (Figure 3-2). Likewise, leaf area index was positively related to plant available water content in the PMM layer in 2011 and 2012 (r = 0.83, p = 0.030 and r = 0.80, p = 0.046 respectively) (Table

3-1). There were no significant relationships between plant available water in PMM and tree growth on the OB plots in 2011 or 2012 (Table 3-1).

On TS plots soil organic carbon content in the PMM was positively related to plant available water content in the PMM layer in 2011 (r = 0.87, p = 0.020) (Figure 3-2); there was the same trend in 2012 but it was not statistically significant (Table 3-1). PMM layer thickness was also positively related to plant available water storage in the layer in 2011 and 2012 (r = 0.96, p = 0.004 and r = 0.95, p=< 0.005, respectively) (Figure 3-2).

On OB plots PMM soil organic carbon content was not related to plant available water content in the PMM in 2011 and 2012 (Table 3-1). PMM soil organic carbon content was positively related to tree growth (Figure 3-4), including aboveground biomass increment (r = 0.82, p = 0.036), 5-year height growth (r = 0.84, p = 0.028) and leaf area index (r = 0.94, p = 0.002) (Table 3-1). PMM layer thickness was also not significantly related to plant available water storage in the PMM layer but there was a positive trend (Table 3-1).

3.3 Water stress relationships with site characteristics and tree growth

Tree water stress characteristics are in Table A-7 of Appendix A. On TS plots, predawn shoot water potential ranged from -0.6 to -1.1 MPa and -0.3 to -0.8 MPa in August 2011 and 2012, respectively. Foliar $\delta^{13}C$ ranged from -26.76 to -28.17 ‰ in 2010. Foliar $\delta^{13}C$ samples for 2011 were collected twice in October 2011 and 2012 and the results ranged from -26.45 to -28.05 ‰ and -25.21 to -27.93‰, respectively. Foliar $\delta^{13}C$ ranged from -25.41 to -28.20 ‰ in 2012 (Table A-7 of Appendix A).

Predawn shoot water potential was positively related to aboveground biomass increment in August 2011 on TS plots (r = 0.85, p = 0.009) (Figure 3-3) indicating that the more water stress the site experienced, the less the trees grew. Five-year height increment, which was correlated with current height increment (r = 0.78, $p = 0.019$), was also positively related to predawn shoot water potential in August 2011 (r = 0.77, $p = 0.020$). Predawn shoot water potential was also related to leaf area index in 2011 (r = 0.96, $p <= 0.001$). Mean plant available water content in the PMM layer was positively, but not significantly, related to predawn shoot water potential in 2011 (r = 0.71, $p = 0.073$) (Table 3-1).

On OB plots predawn shoot water potential ranged from -0.6 to -1.4 and from -0.8 to -1.4 MPa in August 2011 and 2012, respectively. Foliar $\delta^{13}C$ ranged from -29.4 to -30.82 ‰ in 2010. Foliar $\delta^{13}C$ samples for 2011 were collected twice in October 2011 and 2012 and the results ranged from -28.93 to -30.22 ‰ and -27.19 to -29.02 ‰, respectively. Foliar $\delta^{13}C$ ranged from -26.44 to -28.65 ‰ in 2012 (Table A-7of Appendix A).

August predawn shoot water potential and foliar $\delta^{13}C$ were positively related in 2011 (r = 0.85, $p = 0.031$) (Figure 3-4) indicating that water stress levels on each plot were consistent with both indicators. Foliar $\delta^{13}C$ was also negatively related to plant available water storage in the PMM in 2011 (r = 0.71, $p = 0.036$) meaning that plots indicating more water stress had less plant available water in the PMM throughout the growing season (Figure 3-4). Also, foliar $\delta^{13}C$ was negatively correlated to total soil carbon in the PMM layer, but not significantly (Table 3-1).

4.0 Discussion

4.1 Organic matter content affected water availability

Soil organic matter content is one of the factors that may have caused PMM water availability to vary on TS and OB plots. My results also show that sites with more soil organic carbon in the PMM layer had greater water availability, especially in 2011, the year that was drier than normal (Table 3-1).

Increasing soil organic matter increases water-holding capacity (Hudson, 1994) and particularly, the addition of peat does so as well (Moskal et al., 2001). Furthermore, on sloped sites, soil organic matter would reduce drainage into the substrate layer and reduce run-off. On OB plots, PMM soil organic carbon content was positively related to aboveground biomass increment, 5-year height increment and leaf area index indicating that more organic matter in the PMM is resulting in more tree growth. Soil organic carbon may have also increased tree growth by its nutrient contribution to the PMM (Hemstock, 2010). Although it was not studied by the author, a separate study by Duan et al. (2015) on the same plots show that nitrogen availability may be the leading limiting factor to tree growth on the OB plots.

Peat-mineral mix layer thickness also had a positive trend with water availability, which was expected because increasing volume of PMM will increase the total amount of water held in the layer before drainage into the TS layer. Also, soil water tends to only drain from the PMM into the TS when water content is above field capacity (Naeth et al., 2011; Leatherdale, et al., 2012) because the peat increases the ratio of micropores in the PMM to the TS layer (Porro, 2001) creating a capillary barrier that will increase water-holding capacity in the PMM (Naeth, 2011). So once soil water infiltrates the TS layer, it is likely to continue moving downwards, away from tree roots due to the greater proportion of macropores and low water-holding capacity in TS (Barbour et al., 2007). Additionally, thicker PMM also means greater nutrient supply, and greater effective root zone thickness. Therefore, from a management perspective, it is beneficial to prevent water drainage into the TS layer by increasing the amount of soil organic carbon (peat) in the PMM layer and by increasing the thickness of the PMM layer. I accept my first hypothesis that shallower PMM thickness and lower organic carbon content will decrease water availability.

4.2 Tree growth was affected by water availability

Five-year height increment increased with PMM plant available water content in 2011, but not in 2012 (Table 3-1). There was less precipitation during the growing season in 2011 than there is normally (Figure 3-1) and therefore the trees were likely experiencing water deficient conditions and plots that had more water availability supported greater tree growth. A similar example of lodgepole pine growing more on wetter sites is a study conducted by Comeau and Kimmins (1989). They found that lodgepole pine growing on xeric sites had exhibited less biomass increment than pine growing on mesic sites. Lodgepole pine growth has also been shown to decrease in years with less than average precipitation (Chinn et al., 2008; Cortini et al., 2011). Given that each plot is relatively close to one another geographically, it is assumed each plot received the same amount of precipitation. Thus, it appears that site characteristics influenced the variability of PMM water availability between plots (Table 3-1).

In both years of this study there was a positive relationship between plant available water in PMM and leaf area index on TS plots (Table 3-1) which indicated that greater water availability supported greater leaf area index. As a result, leaf area index supported greater aboveground biomass increment (Table 3-1).

On the OB plots there were no significant relationships between PMM water availability and tree growth in either year of the study, indicating that water availability may not have been the primary limiting factor to growth on these plots. This result may be due to the fine textured OB substrate: high bulk density in the OB substrate (Yarmuch, 2003) and the fact that it was extremely difficult to dig into the substrate during sampling indicated that it was compacted. My bulk density results were similar to what Yarmuch (2003) measured and his comparison with undisturbed Bt horizons in the AOSR showed that the bulk density of the OB was not significantly different than the undisturbed sites. Yet, due to OB's fine texture, the substrate has mostly micropores so drainage into the substrate is reduced and more soil water remains in the PMM. As a result, very few roots were observed in the OB layer while digging soil pits (data not shown) and likewise Lazorko (2012) found that only 1.3 to 2.2% of total root length in the soil profile was found in the OB layer. Thus, other characteristics of the PMM layer may be more limiting on OB substrates. For instance, Duan et al. (2015) found that nitrogen was limiting tree growth on OB sites. On the other hand, PMM soil organic carbon content was related to tree growth (aboveground biomass increment and five-year height increment) in 2011, but not in 2012 (Table 3-1). With 2011 being the drier year (Figure 3-1), it appears that the plots with increased water holding capacity (greater PMM soil organic carbon content) may have buffered the drier conditions by holding more water in the soil.

On TS plots, I can accept my second hypothesis that reclaimed forest ecosystems with lower growth rates were affected by lower water availability. However, on OB plots I reject this hypothesis because lower growth rates were not related to lower water availability in the years it was assessed.

4.3 Predawn shoot water potential and ^{13}C stable isotope composition reflected plant-water relationships

Predawn shoot water potential was related to tree growth (aboveground biomass increment and 5-year height increment) and PMM water availability in 2011 on TS plots (Table 3-1). Predawn shoot water potential was only measured during a short period of the growing season, but it was directly related to available soil water and this relationship was also found in a study by Dang et al. (1997). Lower shoot water potential can cause stomatal closure (Ludlow, 1980; Osonubi and Davies, 1980) and thus reduce photosynthetic activity (Teskey et al., 1986; Ni and Pallardy, 1992). These functions that mitigate water stress, stomatal closure and reduced photosynthetic activity, also reduced tree growth (Bréda et al., 2006), as I observed in the relationships between predawn shoot water potential and tree growth on TS plots in 2011. In 2012, these relationships were not observed likely because 2012 was a wetter year and other limiting factors may have been affecting tree growth. On TS sites I accept my third hypothesis that tree growth is related to indicators of water stress.

August predawn shoot water potential and foliar $\delta^{13}C$ were positively related in 2011 on OB plots. This relationship indicates that in the drier than usual year (Figure 3-1) some plots experienced more water stress than others and both of these indicators of water stress expressed that. As mentioned above, predawn shoot water potential is basically a snapshot of the tree water status whereas the foliar $\delta^{13}C$ provides information for the whole growing season (Warren et al., 2001). Although these water stress indicators were not directly related to tree growth in either year, foliar $\delta^{13}C$ was negatively related to plant available water storage in the PMM layer indicating that plots with less water availability had trees with higher $\delta^{13}C$ in their leaves. This result indicates that the stomata were closed more often because there was insufficient water availability for transpiration. Therefore, some plots were experiencing water stress in 2011 but there may have been other more severe limiting factors that reduced growth. Thus, I cannot accept my third hypothesis that reclaimed forest ecosystems with lower growth rates exhibit greater water stress, as indicated by more negative shoot water potential and a higher foliar $\delta^{13}C$ because they were not directly related to tree growth. However, since foliar $\delta^{13}C$ was related to plant available water storage there is indication that water stress is occurring in the OB plots, but it may not be the most limiting factor.

5.0 Conclusions

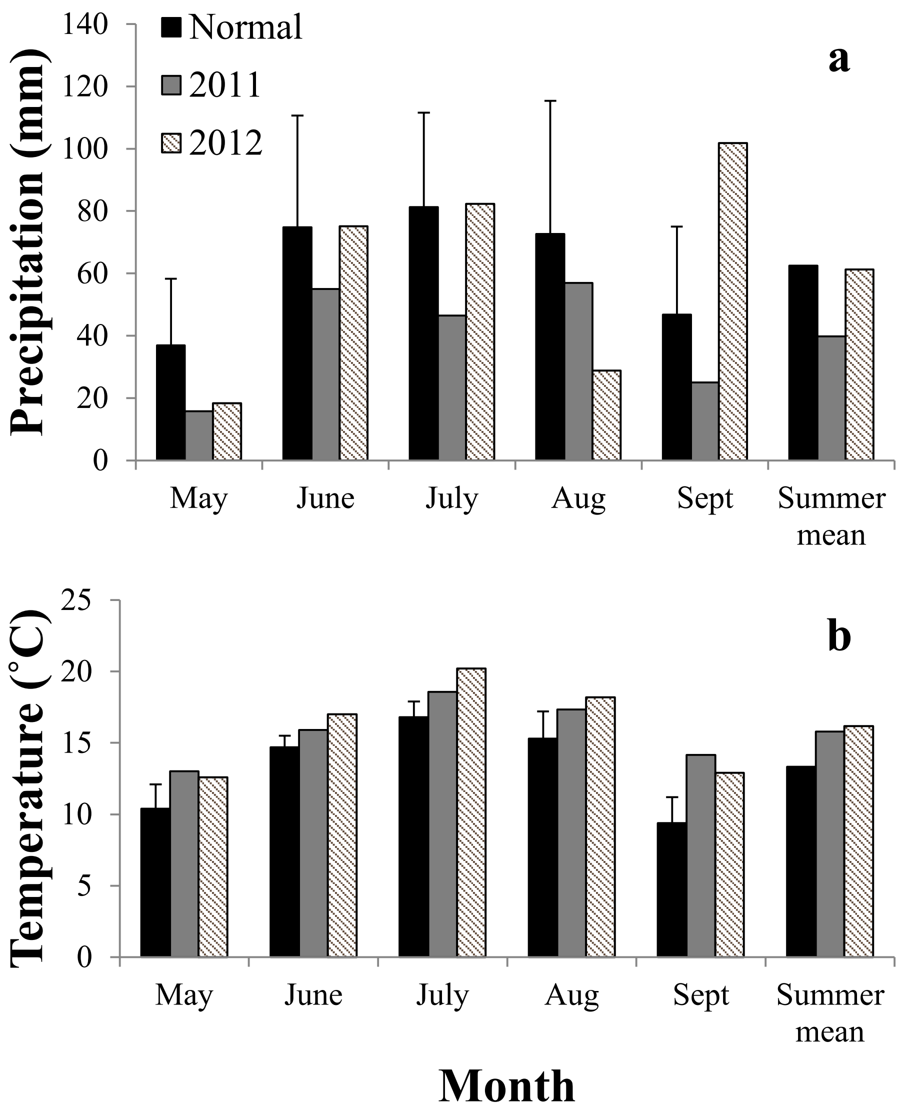
In the studied oil sands reclaimed forest ecosystems, tree growth was limited by water availability in 2011, the drier year. On TS substrates, sites with high organic matter content or thick PMM layers had substantially greater water availability and resultantly more tree growth. On OB sites, where water availability was not the most likely limiting factor, sites that had higher soil organic carbon content had more tree growth. Therefore, future oil sands land reclamation practices should consider to apply sufficient PMM, in quantity and quality, to help reduce water stress in dry years to ensure greater reclamation success in the AOSR.

Table 3-1 Coefficient of determination (R^2)and probability (p) for relationships between tree growth increments, water stress indicators and site characteristics on tailings sand and overburden substrate plots in the Athabasca oil sands region in 2011 and 2012.

Substrate type	Tailings Sand				Overburden			
Dependent / independent variable	2011		2012		2011		2012	
	R^2	p	R^2	p	R^2	p	R^2	p
Aboveground biomass increment								
Predawn shoot water potential, August	**0.85**	**0.009**	0.02	0.721	0.04	0.696	0.19	0.245
Leaf area index	**0.78**	**0.013**	**0.75**	**0.002**	0.01	0.869	0.01	0.822
Soil organic carbon content, PMM[1]	0.07	0.603	0.19	0.242	**0.82**	**0.036**	0.10	0.44
5-year height increment								
Predawn shoot water potential, August	**0.77**	**0.020**	0.08	0.457	0.01	0.848	0.04	0.631
Current annual height increment	**0.78**	**0.019**	**0.78**	**0.002**	**0.92**	**0.042**	**0.83**	**0.005**
Plant available water content, PMM	**0.99**	**0.001**	**0.78**	**0.019**	0.28	0.363	0.14	0.535
Soil organic carbon content, PMM	0.20	0.378	0.01	0.929	**0.84**	**0.028**	0.09	0.469
Leaf area index								
Predawn shoot water potential, August	**0.96**	**0.001**	0.01	0.812	0.45	0.142	**0.55**	**0.023**
Soil organic carbon content, PMM	0.18	0.404	0.09	0.421	**0.94**	**0.002**	**0.51**	**0.030**
Plant available water content, PMM	**0.83**	**0.030**	**0.80**	**0.046**	0.38	0.193	0.01	0.820
Predawn shoot water potential, August								
Plant available water content, PMM[1]	0.71	0.073	0.30	0.336	0.53	0.102	0.37	0.204
Plant available water content, PMM								
Soil organic carbon content, PMM	**0.87**	**0.020**	0.63	0.109	0.51	0.107	0.06	0.632
Plant available water storage, PMM								
PMM thickness	**0.96**	**0.004**	**0.95**	**0.005**	0.15	0.45	0.58	0.078
Soil organic carbon content, PMM	0.36	0.283	0.36	0.286	0.34	0.228	0.01	0.878
Foliar $\delta^{13}C$								
Predawn shoot water potential, August	0.08	0.589	0.17	0.271	**0.85**	**0.031**	0.00	0.990
Plant available water storage, PMM	0.004	0.923	0.25	0.801	**-0.71**	**0.036**	0.46	0.141
Total soil organic carbon, PMM	0.17	0.414	0.16	0.294	-0.03	0.748	0.04	0.616

[1]PMM refers to peat-mineral mix cover soil.

Figure 3-1 Mean monthly precipitation (a) and temperature (b) in 2011 and 2012 at Suncor Energy Inc. Lease 86 / 17 in the Athabasca oil sands region. Normal is the mean from 1971 – 2000 (Environment Canada, 2008). Bars represent standard error of the mean.



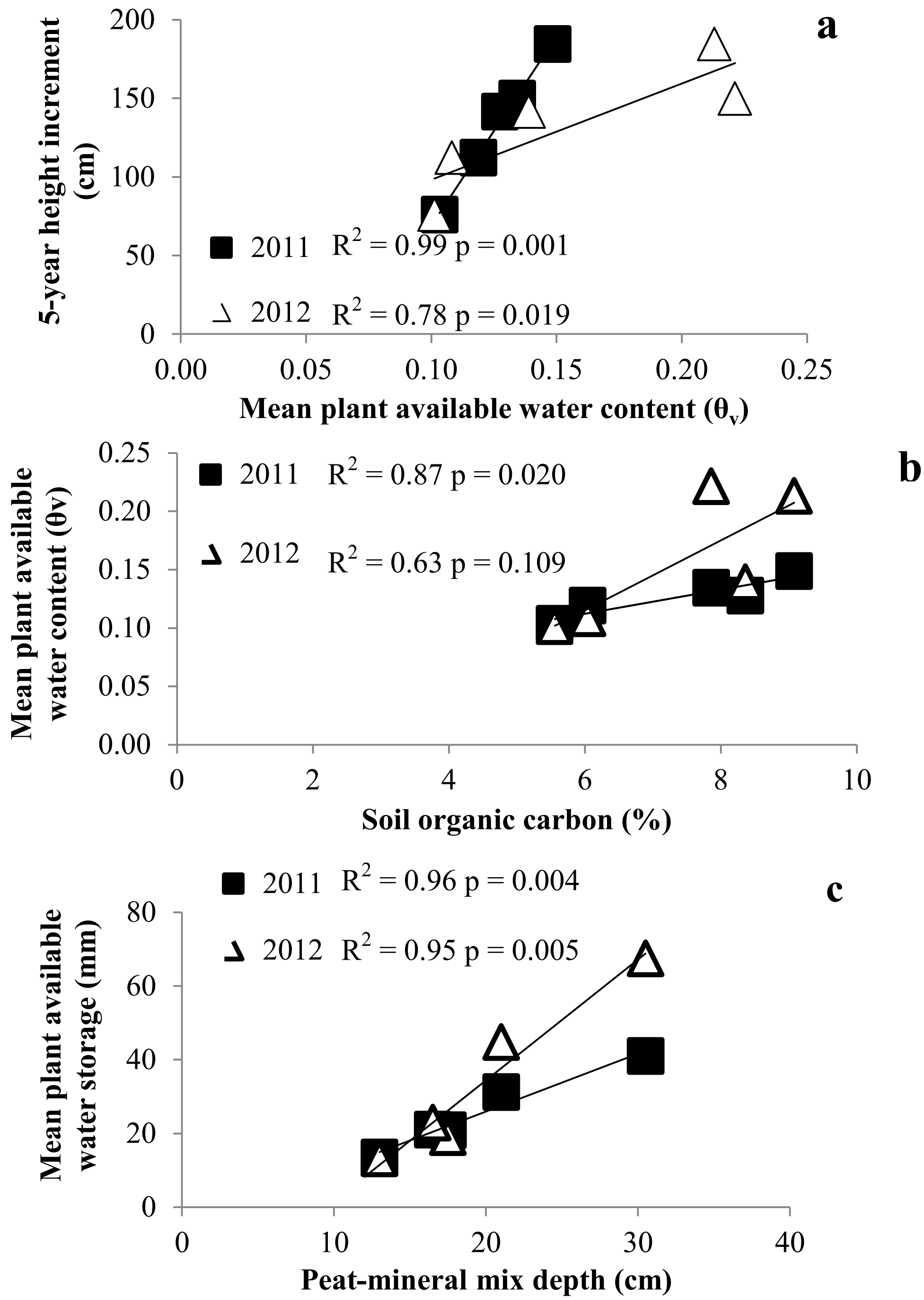


Figure 3-2. Linear regression with (a) 5-year height increment of lodgepole pine and mean plant available water content and (b) mean plant available water content and soil organic carbon in the peat-mineral mix layer on tailings sand plots; (c) linear regression with mean plant available water storage in the peat-mineral mix layer and peat-mineral mix depth on tailings sand plots. All relationships have a p-value less than 0.05. Solid trend line represents line of best fit.

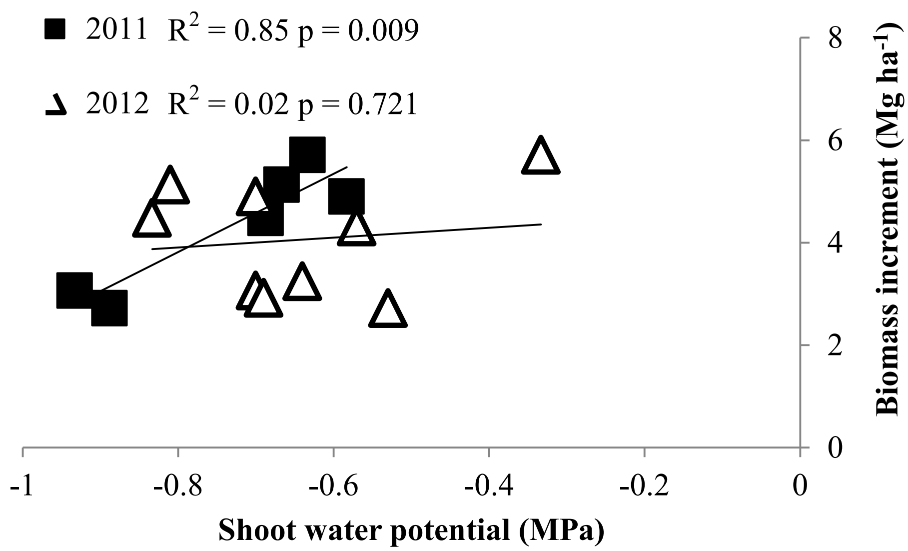


Figure 3-3 Linear regression of aboveground biomass increment and predawn shoot water potential in August of lodgepole pine on tailings sand plots.

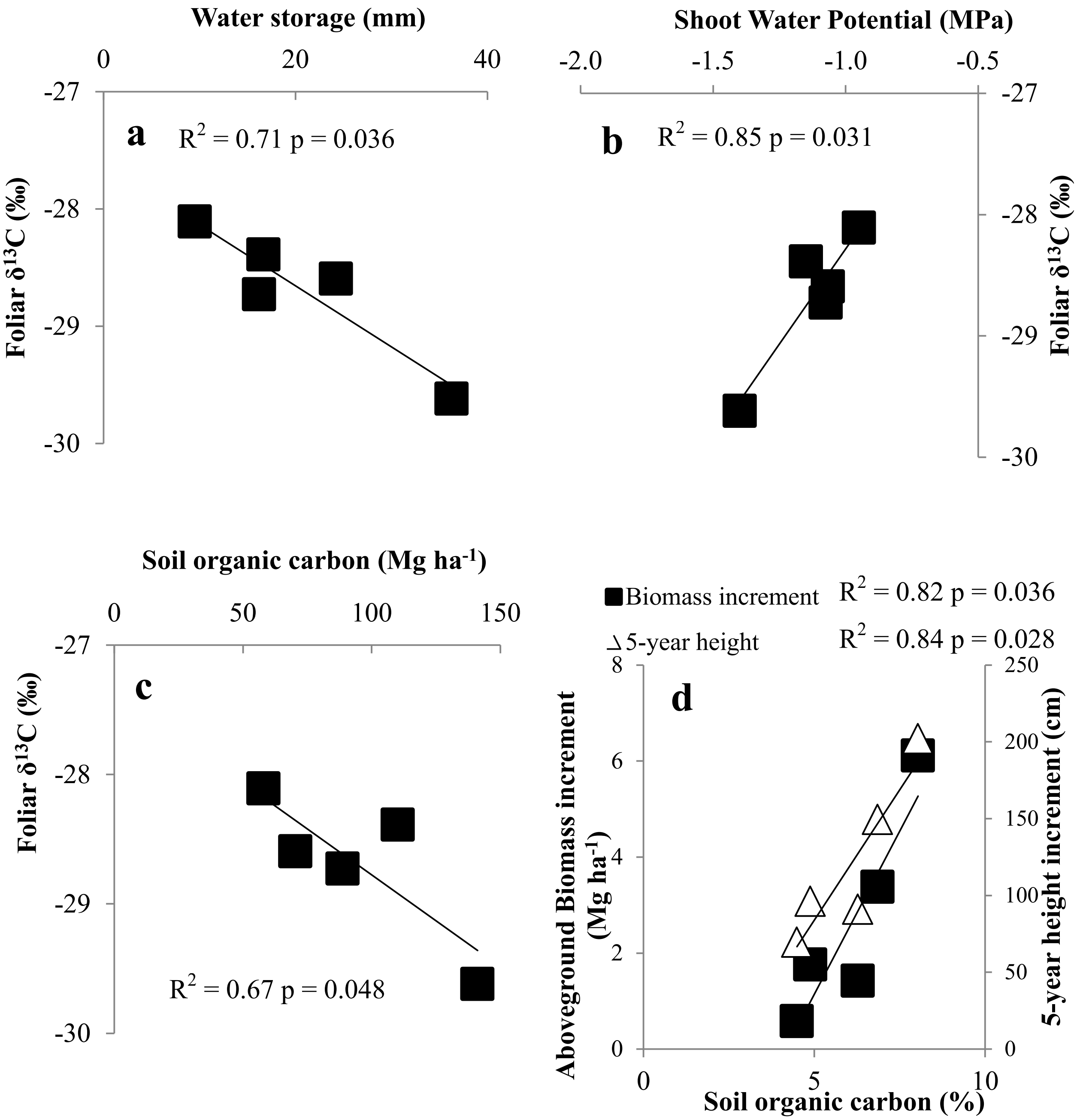


Figure 3-4 Linear regression with (a) white spruce foliar δ^{13}C and plant available water storage in the peat-mineral mix layer in 2011, (b)white spruce foliar δ^{13}C and predawn shoot water potential in August 2011, (c) white spruce foliar δ^{13}C and total soil organic carbon in the peat mineral mix layer and (d) soil organic carbon content in the peat mineral mix layer and aboveground biomass increment and 5-year height increment in 2011on overburden plots in the Athabasca oil sands region.

4. Chapter 4 Synthesis, conclusions and future research

1.0 Overview of study objectives

Novel ecosystems in the Athabasca oil sands region (AOSR) are created through the reclamation of land disturbed following oil sands mining activities. The main purpose of land reclamation is to restore disturbed areas to land capability equivalent to that existed before the disturbance, as required by Alberta's *Environmental Protection and Enhancement Act.* Soil properties, such as soil water and nutrient availability (Natural Regions Committee, 2006; Bothe and Abraham, 1993), salinity (Kessler et al., 2010; Purdy and Macdonald, 2007) and compaction are factors that can limit tree growth and plant community development in these novel ecosystems, and ultimately restrict mining companies from obtaining reclamation certification from the Alberta government. The majority of novel ecosystems in the AOSR are reclaimed forest ecosystems and were established less than 30 years ago. Most research conducted about these novel ecosystems occurs on newly established sites (i.e., 1 to 5 years old). Therefore, there was a need to understand how these novel ecosystems develop after site establishment and to understand what factors may limit tree growth on these sites. In consideration of these needs, the objectives of the study were: 1) to characterize understory plant communities and their relationships with tree performance in a range of plots that constitute a productivity gradient in reclaimed forest ecosystems within the AOSR, and 2) to study water availability as a potential limiting factor for tree growth in novel ecosystems within the AOSR. The study area was in reclaimed forest ecosystems of Suncor Energy Inc. Lease 86/17, just north of Fort McMurray. The study in Chapter 2 was conducted to achieve the first objective; soil properties in the peat mineral mix and substrate layers were measured as well as tree growth over two growing seasons. Relationships between understory plant communities and site characteristics were then examined. The study in Chapter 3 was conducted to achieve the second objective, which was to compare water availability with other soil physical properties and tree growth. Tree growth was also compared with water stress indicators to investigate whether water stress was related to tree growth.

2.0 Summary of the research results

2.1 Site characteristics, understory plant communities and tree growth

Plots with TS substrate had understory plant communities with more shrub, grass and total cover than plots with overburden (OB) substrate; herbaceous layer cover was not related to substrate type. In the peat mineral mix cover soil, inorganic nitrogen content and water availability were greater on TS substrate plots than on OB substrate plots. These results suggest that, in general, TS substrate plots were able to support greater understory plant community cover. It was also observed that tree and understory roots penetrated into the TS substrate, but few roots penetrated into the OB substrate. Therefore, roots on TS substrate plots were able to access a greater soil volume as they searched for soil water and nutrients whereas roots on OB substrate plots were more restricted to the peat mineral mix layer of the soil profile. The greater the soil volume for roots to access, the more potential for tree growth (Jung et al., 2014) and greater understory cover (Finér et al., 2007).

Foliar nitrogen and phosphorus concentrations in understory species were positively related to tree aboveground biomass increment which indicated that on plots with understory species that had high foliar nutrient concentrations also had trees that grew at faster rates. Decomposition of litterfall from understory species could have been a factor in this positive relationship. A study by Nilsson and Wardle (2005) showed that annual litter fall from understory species decomposed quickly and thus increased buildup of organic matter and nutrients in the soil. Their finding implies that understory litterfall in my plots may act as a nutrient source in the soil and that plots with higher litterfall nutrient concentrations result in better tree performance.

2.2 Water availability and tree growth

In the year with less than average growing season precipitation, 2011, tree growth was limited by water availability. Plots that had higher PMM soil organic matter content and thicker cover soil layers had greater water availability, which in turn had greater tree growth. Water stress indicators such as predawn shoot water potential and $\delta^{13}C$ did not directly correlate with tree growth but they did correlate with each other. This correlation indicates that the trees were under water stress but there may have been factors more limiting than water availability that affected tree growth.

3.0 Conclusions

3.1 Site characteristics, understory plant communities and tree growth

This study provided insight into what happens in the understory of reclaimed forest ecosystems 10 to 20 years after site establishment in the AOSR. Understory plant community characteristics were correlated with soil properties and were also correlated with tree performance. In general, the understory in reclaimed forest ecosystems is a small amount of the biomass when compared to trees biomass but its litterfall was related to tree growth and should be a focus of further study in reclaimed forest ecosystems. In addition, these results suggest that reclamation practioners who need to do a quick and representative assessment of cover soil fertility, could simply evaluate understory cover.

3.2 Water availability and tree growth

Precipitation in 2011 was less than the 30 year average (Environment Canada, 2013) and this was the year when tree growth was correlated with water availability. The plots with thicker cover soil and greater soil organic carbon content (i.e., peat) were able to hold more plant available water and thus able to buffer the effects of less precipitation. When considering that trees repeatedly exposed to water stress will experience less growth and potentially mortality (Davies and Zhang, 1991; Bréda et al., 2006), the AOSR is subject to moderate water deficits for short periods during the growing season (Natural Regions Committee, 2006) and that climate change is expected to increase weather condition severity (e.g., longer periods of water deficits), some reclaimed forest ecosystems in the AOSR are at risk of not being successfully reclaimed. In order to successfully reclaim forest ecosystems and, also, achieve reclamation certification, reclamation practioners need to create self-sustaining novel ecosystems. This endeavor should include re-constructing sites with thick cover soils and high soil organic carbon contents (i.e., more peat) so that the rooting zone of the soil can hold more water for root uptake. Additionally peat and litterfall decomposition can potentially be a source of nutrient for root uptake.

4.0 Suggestions for future research

4.1 The understory's influence on reclamation success

Muller (2003) summarized many studies in the literature and showed that foliar nutrient concentrations were 30% higher in understory species than in tree species and that litterfall of understory species decomposed more than twice as fast as that of tree species in natural ecosystems. It would be interesting to determine if there are the same trends in reclaimed forest ecosystems. The foliar nutrient concentrations in understory vegetation in this study could be compared with foliar nutrient concentrations in tree species measured in a parallel study (Duan et al., 2015). Decomposition rates of understory and tree species litterfall could also be measured and compared by placing wire mesh bags of each litterfall type on the study sites at the beginning of the growing season. The bags would be collected at the end of the growing season and measured to determine decomposition rates. Results of such a study could provide greater insight into the understory's influence in the reclaimed forest ecosystems and if the understory's influence is affected by substrate type.

4.2 Why water availability was low in some reclaimed soils

The correlation between water availability and tree growth does not necessarily prove causation. To determine if water availability truly is the most limiting factor in these reclaimed forest ecosystems, an irrigation study should be undertaken to test the question. Study duration should be over multiple growing seasons to determine if greater or less than average precipitation has a limiting effect on tree growth. If tree growth on irrigated sites was greater than the control sites, it would show that water availability is limiting growth and reclamation practioners would be advised to utilize measures that increase water availability in the cover soil such as increasing cover soil thickness and organic matter content (i.e., adding more peat).

Appendix

Table A- 1 Site characteristics of tailings sand and overburden substrate plots in the Athabasca oil sands region. Standard errors of the mean in parenthesis. Plot TS3 was removed from the mean plant available soil water content calculation due to a faulty sensor.

Plot[1]	Year[2]	Aspect	Slope	Slope position	Peat-mineral mix: Thickness	Bulk density	Soil strength	Total C	Total C	Total N	NH_4	Plant available soil water[3,4]: content 2011	content 2012	storage 2011	storage 2012
		(°)	(%)		(cm)	($g\ cm^{-3}$)	($kg\ m^{-2}$)	(%)	($Mg\ ha^{-1}$)	(%)	($mg\ kg^{-1}$)	($v\ v^{-1}$)		(mm)	
TS1	1996	114	23	upper	17.5	0.77	0.8	6.0	81.5	0.29	3.14	0.12	0.11	21	19
TS2	1991	148	27	upper	13.0	1.09	2.0	5.6	78.8	0.23	2.17	0.10	0.10	13	13
TS 3	1996	55	22	upper	15.5	1.15	0.6	3.0	53.8	0.15	7.74	0.02	0.02	4	3
TS 4	1992	190	42	mid	30.5	0.82	0.7	7.9	196.6	0.29	7.60	0.04	0.22	41	67
TS 5	1991	252	25	upper	16.5	0.92	1.0	8.4	126.9	0.41	3.03	0.13	0.14	21	23
TS 6	1991	2	30	upper	21.0	0.61	0.7	9.1	116.3	0.37	10.47	0.06	0.21	31	45
TS 7	1992	190	37	mid	12.0	1.40	1.0	1.5	25.4	0.06	8.62	-	-	-	-
TS 8	1991	122	24	upper	22.0	1.04	1.2	8.5	195.0	0.36	3.14	-	-	-	-
TS 9	1996	58	21	mid	29.5	1.22	0.6	5.1	183.8	0.17	3.07	-	-	-	-
Mean			28 (7)		19.7 (6.7)	1.00 (0.25)	0.9 (0.5)	6.1 (2.6)	117.6 (63.4)	0.26 (0.11)	5.44 (2.95)	0.09 (0.02)	0.16 (0.06)	25.4 (10.8)	33.4 (22.3)
OB1	1982	218	35	upper	19.5	0.9	0.8	6.3	110.2	0.25	2.27	0.09	0.10	17	19
OB2	1991	260	3	crest	9.5	1.36	1.9	4.5	58.0	0.18	2.45	0.10	0.08	10	8
OB3	1991	94	13	lower	24.5	1.18	1.9	4.9	141.1	0.17	1.94	0.15	0.19	36	46
OB4	1992	25	16	lower	13.5	0.76	1.0	6.9	70.3	0.25	4.53	0.18	0.20	24	27
OB5	1992	296	3	toe	12.0	0.92	1.5	8.0	88.7	0.37	4.67	0.14	0.13	16	16
OB6	1984	346	30	mid	21.5	0.32	0.5	18.4	126.8	1.04	6.46	0.02	0.10	5	22
OB7	1991	275	32	upper	47.5	0.95	1.4	5.6	251.7	0.19	2.48	-	-	-	-
OB8	1992	176	2	level	26.0	1.11	1.0	17.0	490.7	0.88	4.91	-	-	-	-
OB9	1992	71	3	level	20.0	0.87	1.6	5.3	92.1	0.15	5.04	-	-	-	-
Mean			15 (14)		21.6 (11.2)	0.93 (0.29)	1.3 (0.5)	8.6 (5.3)	158.9 (136.9)	0.39 (0.31)	3.86 (1.51)	0.11 (0.06)	0.13 (0.05)	18.0 (10.9)	23.0 (12.9)

[1] TS and OB are tailings sand substrate and overburden substrate, respectively.

[2]Year is when trees were planted following soil reconstruction.

[3] Plant available water content and storage was not measured on plots TS9, TS8, TS9, OB7, OB8 and OB9 because equipment was unavailable.
[4] Plot TS3 was removed from the mean plant available soil water content and storage calculation due to a faulty sensor.

Table A- 2 Mean understory cover (%) in on tailings sand and overburden substrate plots in the Athabasca oil sands region.

Plot[1]	Shrub	Herbaceous	Grass	Total cover
TS1	9.4	14.0	24.8	48.2
TS2	1.0	21.2	9.8	32.0
TS3	5.6	1.7	3.6	10.9
TS4	22.0	2.4	50.2	74.6
TS5	0.0	10.5	2.0	12.5
TS6	1.0	49.2	36.6	86.8
TS7	13.4	9.0	43.2	65.6
TS8	9.4	13.2	3.6	26.2
TS9	10.6	22.0	4.8	37.4
Mean	8.0	15.9	19.8	43.8
OB1	0.0	15.2	0.6	15.8
OB2	0.0	16.0	6.4	22.4
OB3	0.4	10.8	6.2	17.4
OB4	6.0	5.9	13.2	25.1
OB5	9.0	11.2	10.0	30.2
OB6	0.1	0.4	0.0	0.5
OB7	0.2	2.2	0.0	2.4
OB8	20.4	20.6	0.6	41.6
OB9	0.0	15.8	0.2	16.0
Mean	4.0	10.9	4.1	19.0

[1]TS and OB are tailings sand substrate and overburden substrate, respectively.

Table A- 3 Plant community characteristics on tailings sand and overburden substrate plots in the Athabasca oil sands region. Standard errors of the mean are in parenthesis.

Plot[1]	Species richness	Species evenness	Shannon-Wiener Index
TS1	6.2 (2.3)	0.36 (0.18)	1.13 (0.46)
TS2	3.6 (1.5)	0.55 (0.35)	0.82 (0.36)
TS 3	5.8 (2.6)	0.43 (0.14)	0.98 (0.68)
TS 4	3.8 (1.3)	0.40 (0.22)	0.62 (0.17)
TS 5	4.6 (0.9)	0.62 (0.29)	1.18 (0.42)
TS 6	5.4 (1.1)	0.36 (0.20)	1.17 (0.37)
TS 7	4.0 (1.0)	0.49 (0.22)	1.00 (0.34)
TS 8	2.6 (0.5)	0.70 (0.32)	0.70 (0.31)
TS 9	6.6 (2.3)	0.52 (0.21)	1.41 (0.34)
Mean	4.7 (1.3)	0.49 (0.12)	1.00 (0.25)
OB1	7.6 (1.5)	0.54 (0.16)	1.51 (0.15)
OB2	5.6 (1.1)	0.42 (0.17)	1.13 (0.48)
OB3	8.0 (1.2)	0.28 (0.03)	0.92 (0.16)
OB4	5.8 (1.9)	0.28 (0.09)	0.83 (0.31)
OB5	5.8 (0.4)	0.33 (0.14)	0.91 (0.14)
OB6	1.0 (0.7)	0.94 (0.13)	0.10 (0.22)
OB7	3.2 (1.1)	0.44 (0.27)	0.58 (0.49)
OB8	8.4 (2.5)	0.47 (0.16)	1.45 (0.29)
OB9	5.4 (1.7)	0.40 (0.09)	0.99 (0.40)
Mean	5.6 (2.4)	0.46 (0.20)	0.94 (0.43)

[1] TS and OB are tailings sand substrate and overburden substrate, respectively.

Table A- 4 Foliar nutrient concentrations of sweet clover, dandelion and fireweed on tailings sand and overburden substrate plots in 2011, in the Athabasca oil sands region. Standard errors of the mean are in parenthesis.

Plot[1]	Sweet clover						Dandelion					
	C (%)	N (%)	P (%)	K (%)	Mg (%)	Ca (%)	C (%)	N (%)	P (%)	K (%)	Mg (%)	Ca (%)
TS1	41.70	3.93	0.30	1.90	1.01	6.01	41.28	2.71	0.27	3.10	0.65	1.50
TS2	41.89	3.51	0.26	1.65	0.63	6.49	39.58	3.69	0.27	3.47	0.38	2.32
TS3	43.08	4.11	0.18	1.81	0.33	3.47	41.22	2.45	0.25	2.96	0.74	1.79
TS4	40.94	3.68	0.17	1.66	0.51	3.94	39.59	3.03	0.32	2.91	0.44	2.54
TS5	41.06	3.81	0.23	0.95	0.65	4.18	38.46	2.41	0.38	2.71	0.49	3.05
TS6	42.30	3.87	0.24	1.19	0.40	3.61	39.62	2.57	0.41	4.55	0.45	1.73
Mean	41.83 (0.80)	3.82 (0.21)	0.23 (0.05)	1.53 (0.37)	0.59 (0.24)	4.62 (1.30)	39.96 (1.09)	2.81 (0.49)	0.32 (0.07)	3.28 (0.67)	0.53 (0.14)	2.16 (0.59)
	Sweet clover						Fireweed					
OB1	-	-	0.22	1.26	0.67	4.36	43.68	1.06	0.12	0.50	0.71	2.11
OB2	40.66	3.95	0.22	1.31	0.82	3.63	48.01	1.42	0.22	0.55	0.66	2.01
OB3	41.99	4.34	0.26	1.48	0.62	3.28	43.89	1.11	0.11	0.63	0.56	1.94
OB4	41.74	4.17	0.20	1.66	0.38	3.26	44.46	1.34	0.29	1.08	0.68	1.95
OB5	41.14	4.15	0.23	1.28	0.57	3.51	43.75	1.97	0.49	1.00	0.92	1.73
OB6	39.50	3.13	0.12	1.16	0.50	4.70	42.90	0.99	0.09	0.95	0.73	1.85
Mean	41.01 (0.99)	3.95 (0.48)	0.21 (0.05)	1.36 (0.18)	0.59 (0.15)	3.79 (0.60)	44.45 (1.82)	1.32 (0.36)	0.22 (0.15)	0.79 (0.25)	0.71 (0.12)	1.93 (0.13)

[1] TS and OB are tailings sand substrate and overburden substrate, respectively.

Table A- 5 Foliar nutrient concentrations of fireweed and dandelion on tailings sand and overburden plots in 2012, in the Athabasca oil sands region. Standard errors of the means are in parenthesis. Cells with a dash indicate foliar samples for the plant species were not available on that plot.

Plot[1]	Fireweed						Dandelion					
	C (%)	N (%)	P (%)	K (%)	Mg (%)	Ca (%)	C (%)	N (%)	P (%)	K (%)	Mg (%)	Ca (%)
TS1	44.63	2.14	0.19	0.81	0.83	2.41	41.62	2.58	0.24	3.70	0.92	2.50
TS2	-	-	-	-	-	-	-	-	-	-	-	-
TS3	44.90	2.84	0.34	1.82	0.83	2.24	40.15	2.12	0.19	3.29	1.02	2.48
TS4	-	-	-	-	0.81	2.19	39.05	2.13	0.42	5.74	0.65	2.33
TS5	-	-	0.32	1.10	0.61	2.48	39.48	2.14	0.63	4.14	0.70	2.75
TS6	43.11	3.03	0.27	1.99	0.76	2.05	40.12	2.75	0.37	4.45	0.70	2.22
TS7	-	-	-	-	-	-	-	-	-	-	-	-
TS8	44.24	1.59	0.23	1.11	0.68	2.58	39.29	1.99	0.46	5.29	0.61	2.69
TS9	45.80	2.07	0.26	1.06	0.59	1.92	39.60	2.20	0.22	3.45	0.86	2.57
Mean	44.54	2.33	0.27	1.32	0.73	2.27	39.90	2.27	0.36	4.29	0.78	2.51
	(0.98)	(0.59)	(0.06)	(0.47)	(0.10)	(0.24)	(0.86)	(0.28)	(0.16)	(0.93)	(0.15)	(0.19)
OB1	39.34	2.03	0.41	1.61	0.80	2.21	42.97	2.03	0.26	6.56	0.57	2.31
OB2	53.16	2.97	0.45	1.61	0.66	2.21	45.16	2.26	0.59	5.79	0.51	2.17
OB3	39.54	2.05	0.59	2.00	0.78	2.27	42.92	2.16	0.50	5.75	0.66	2.68
OB4	39.38	1.94	0.33	1.73	0.66	2.13	43.90	2.02	0.51	6.05	0.48	2.34
OB5	38.66	2.01	0.66	1.77	0.81	2.16	43.73	2.35	0.87	5.99	0.63	2.62
OB6	38.23	1.85	0.35	2.40	0.68	1.75	44.09	2.42	0.28	5.77	0.66	2.91
OB7	40.25	2.64	0.68	1.83	0.66	2.45	42.96	2.58	0.77	6.19	0.46	2.30
OB8	40.06	1.99	0.22	1.91	0.72	1.97	44.19	2.40	0.20	6.14	0.48	2.39
OB9	39.74	2.31	0.29	3.60	0.51	2.55	44.82	2.23	0.28	5.50	0.53	2.87
Mean	40.93	2.20	0.44	2.05	0.70	2.19	43.86	2.27	0.47	5.97	0.55	2.51
	(4.63)	(0.37)	(0.17)	(0.63)	(0.10)	(0.24)	(0.81)	(0.19)	(0.24)	(0.31)	(0.08)	(0.27)

[1] TS and OB are tailings sand substrate and overburden substrate, respectively.

Table A- 6 Lodgepole pine and white spruce height, diameter at breast height (DBH), aboveground biomass (AB) and 5-year height increment measurements on tailings sand and overburden plots, respectively, in 2011 and 2012. Increment refers to tree growth during the study period from July 2011 – October 2012. Numbers in parenthesis is the standard error of the mean.

Plot[1]	Height (m) 2011	Height (m) 2012	Height inc[2] ($m\ yr^{-1}$)	DBH (cm) 2011	DBH (cm) 2012	DBH inc[2] ($cm\ yr^{-1}$)	AB ($Mg\ ha^{-1}$) 2011	AB ($Mg\ ha^{-1}$) 2012	ABI[2] ($Mg\ ha^{-1}\ yr^{-1}$)	5-yr height inc[2] (cm)	Leaf area index ($m^2\ m^{-2}$)	Stand density ($trees\ ha^{-1}$)
TS1	3.25 (0.71)	3.39 (0.73)	0.14 (0.08)	5.2 (1.5)	5.9 (1.6)	0.68 (0.22)	8.8	11.8	3.1	112 (32)	0.80 (0.66)	2000
TS2	3.54 (1.05)	3.67 (1.08)	0.14 (0.11)	5.3 (2.2)	5.6 (2.3)	0.28 (0.17)	14.1	16.8	2.7	76 (26)	0.62 (0.05)	2300
TS3	4.31 (0.86)	4.58 (0.84)	0.26 (0.23)	7.3 (2.5)	8.0 (2.5)	0.64 (0.26)	23.6	28.7	5.1	149 (32)	2.60 (0.03)	2300
TS4	4.78 (0.35)	5.02 (0.38)	0.25 (0.14)	7.8 (1.3)	8.2 (1.3)	0.48 (0.36)	32.8	37.3	4.5	150 (22)	2.70 (0.32)	2700
TS5	5.10 (0.76)	5.36 (0.82)	0.26 (0.17)	7.7 (1.7)	8.4 (1.8)	0.69 (0.33)	27.3	33.0	5.7	141 (64)	2.67 (0.72)	2300
TS6	5.27 (0.74)	5.54 (0.72)	0.27 (0.22)	8.8 (2.1)	9.3 (2.2)	0.54 (0.21)	35.0	39.9	4.9	185 (37)	3.23 (0.21)	2100
TS7	6.24 (0.83)	6.48 (0.82)	0.24 (0.13)	9.2 (1.2)	9.5 (1.2)	0.35 (0.14)	35.5	38.8	3.2	159 (25)	2.14 (0.32)	2300
TS8	4.47 (1.00)	4.69 (1.01)	0.22 (0.14)	6.6 (2.3)	7.3 (2.4)	0.62 (0.19)	19.4	23.7	4.3	122 (29)	2.15 (0.66)	2100
TS9	3.13 (0.43)	3.31 (0.39)	0.18 (0.09)	4.7 (1.0)	5.2 (1.1)	0.56 (0.14)	9.0	11.9	2.9	112 (20)	0.80 (0.25)	2600
Mean	4.45 (1.03)	4.67 (1.07)	0.22 (0.05)	7.0 (1.6)	7.5 (1.6)	0.54 (0.14)	22.8 (10.6)	26.9 (6.1)	4.0 (1.09)	134 (32)	1.97 (0.98)	2300 (216)
OB1	6.19 (1.34)	6.10 (1.31)	N/A[3]	7.6 (1.9)	7.8 (2.0)	0.20 (0.11)	25.5	26.9	1.42	91 (38)	2.13 (0.28)	2000
OB2	2.59 (0.84)	2.70 (0.87)	0.11 (0.06)	2.9 (1.6)	3.1 (1.7)	0.24 (0.11)	5.5	6.1	0.58	70 (31)	1.04 (0.49)	2700
OB3	3.91 (0.97)	4.06 (1.04)	0.15 (0.10)	4.9 (1.6)	5.1 (1.6)	0.27 (0.16)	17.1	18.9	1.76	96 (23)	1.83 (0.67)	3200
OB4	5.40 (0.88)	5.61 (0.93)	0.21 (0.13)	6.5 (1.6)	6.8 (1.6)	0.38 (0.14)	26.6	30.0	3.38	149 (33)	2.13 (0.23)	2800
OB5	5.26 (0.71)	5.68 (0.8)	0.41 (0.21)	7.3 (1.6)	8.0 (1.7)	0.64 (0.19)	23.8	29.9	6.11	202 (34)	2.72 (0.06)	1900
OB6	9.29 (1.48)	8.86 (1.31)	N/A[3]	10.9 (2.5)	11.0 (2.5)	0.17 (0.1)	76.4	77.3	1.08	N/A[3]	4.62 (0.23)	2700
OB7	4.32 (0.98)	4.44 (1.02)	0.13 (0.12)	5.3 (1.5)	5.6 (1.6)	0.33 (0.18)	15.5	18.8	3.30	94 (24)	2.61 (0.39)	2600
OB8	4.65 (0.82)	4.92 (0.82)	0.27 (0.14)	6.2 (1.6)	6.7 (1.7)	0.44 (0.8)	20.5	23.7	3.21	128 (32)	2.30 (0.25)	2300
OB9	4.74 (0.87)	4.91 (0.87)	0.18 (0.09)	6.4 (1.9)	6.9 (1.9)	0.45 (0.12)	20.5	23.3	2.80	138 (23)	2.26 (0.13)	2100
Mean	5.15 (1.85)	5.25 (1.69)	0.21 (0.10)	6.4 (2.2)	6.8 (2.2)	0.35 (0.15)	25.7 (20.0)	28.3 (19.8)	2.63 (1.67)	121 (42)	2.40 (0.96)	2478 (405)

[1] TS and OB refer to tailings sand and overburden substrate plots, respectively.

[2] ABI refers to aboveground biomass increment.

[3]N/A is not available because it could not be accurately measured on plot because trees were too tall to be measured with a 5 m height pole and tree tops and whorls could not be viewed with a Vertex III hypsometer due to dense canopy cover.

Table A- 7 Shoot water potential and foliar $\delta^{13}C$ measurements on lodgepole pine and white spruce on tailings sand and overburden plots, respectively, in the Athabasca oil sands region. Shoot water potential (SWP) was recorded predawn (P) and mid-day (M). Numbers in parentheses are standard errors of the mean.

Plot[1]	Shoot water potential (MPa)[2,3,4]							Foliar $\delta^{13}C$ (‰)[5]			
	2011	2012						2011		2012	
	August	June		July		August					
	P	P	M	P	M	P	M	1-yr old	current	1-yr old	current
TS1	-0.93	-0.42	-0.25	-0.19	-0.19	-0.70	-1.20	-27.84	-27.64	-26.48	-27.06
TS2	-0.89	-0.39	-0.24	-0.11	-0.16	-0.53	-1.37	-27.06	-26.45	-25.42	-25.44
TS3	-0.67	-0.29	-0.09	-0.11	-0.12	-0.81	-1.23	-28.00	-28.01	-27.93	-28.20
TS4	-0.69	-0.28	-0.13	-0.14	-0.13	-0.83	-1.44	-26.76	-26.63	-25.21	-25.41
TS5	-0.63	-0.54	-0.42	-0.11	-0.16	-0.33	-1.36	-27.64	-27.69	-25.56	-25.96
TS6	-0.58	-0.35	-0.13	-0.18	-0.17	-0.70	-1.18	-28.17	-28.05	-26.30	-27.60
TS7	N/A	-0.44	-0.14	-0.11	-0.11	-0.64	-1.11	N/A	N/A	-26.37	-26.67
TS8	N/A	-0.35	-0.13	-0.18	-0.17	-0.57	-1.39	N/A	N/A	-26.51	-26.43
TS9	N/A	-0.40	-0.20	-0.16	-0.17	-0.69	-1.27	N/A	N/A	-25.98	-26.62
Mean	-0.73 (0.14)	-0.38 (0.08)	-0.19 (0.10)	-0.14 (0.03)	-0.15 (0.03)	-0.64 (0.15)	-1.28 (0.11)	-27.58 (0.55)	-27.41 (0.70)	-26.15 (1.01)	-26.60 (0.93)
OB1	-1.15	-0.72	-0.95	-0.63	-	-1.11	-2.18	-29.40	-29.08	-27.69	-26.78
OB2	-0.95	-0.46	-0.94	-0.48	-1.19	-0.96	-2.36	-30.16	-28.93	-27.29	-27.13
OB3	-1.40	-0.65	-1.44	-0.57	-1.28	-0.92	-2.14	-30.82	-30.22	-29.02	-28.65
OB4	-1.07	-0.47	-1.16	-0.57	-1.81	-0.81	-2.21	-29.80	-29.39	-27.80	-27.18
OB5	-1.08	-0.54	-1.02	-0.47	-1.45	-0.96	-2.04	-29.79	-29.3	-28.15	-28.02
OB6	-0.61	-0.49	-0.96	-0.59	-0.64	-1.40	-1.62	-29.56	-29.63	-27.65	-27.59
OB7	N/A	-0.52	-1.29	-0.52	-1.49	-0.91	-1.83	N/A	N/A	-28.38	-27.44
OB8	N/A	-0.49	-1.28	-0.56	-1.45	-0.90	-2.13	N/A	N/A	-27.19	-26.44
OB9	N/A	-0.60	-1.20	-0.48	-1.22	-1.04	-2.23	N/A	N/A	-27.55	-26.60
Mean	-1.04 (0.26)	-0.55 (0.09)	-1.14 (0.18)	-0.54 (0.06)	-1.32 (0.34)	-1.00 (0.17)	-2.08 (0.23)	-29.92 (0.51)	-29.43 (0.46)	-27.86 (0.58)	-27.31 (0.71)

[1] TS and OB refer to tailings sand and overburden substrate plots, respectively.
[2] SWP refers to shoot water potential.
[3] Plots TS7, TS8, TS9, OB7, OB8 and OB9 were not sampled for shoot water potential in 2011 because they were added to the study in 2012.
[4] P and M refer to shoot water potential measurements recorded at predawn and mid-day, respectively.
[5] 2011 needles were sampled twice, in October 2011 and October 2012

References

Alberta Energy, 2008. Alberta Government. http://www.energy.alberta.ca/OilSands/791.asp. Accessed on September 18, 2015.

Alberta Environment and Resource Development, 2013. Evaporation and evapotranspiration in Alberta. Data table compendium 1912-2009. Edmonton, Alberta. Alberta Environment and Sustainable Resource Development. http://www.agric.gov.ab.ca/acis/docs/mortons/mortons-evaporation-estimates.pdf Accessed September 17, 2015.

Alberta Environment and Sustainable Resource Development (AESRD). 2013. Oil sands reclamation. http://www.oilsands.alberta.ca/reclamation.html. Accessed September 18, 2015.

Alberta Environment, 2010. Guidelines for reclamation to forest vegetation in the Athabasca oil sands region, 2nd edition. Prepared by the Terrestrial Subgroup of the Reclamation Working Group of the Cumulative Environmental Management Association, Fort McMurray, AB: Alberta Environment.

Alberta Environment. 2013. Oil sands reclamation fact sheet. http://www.oilsands.alberta.ca/FactSheets/Reclamation_FSht_Mar_2013_Dft_1.pdf Accessed on September 18, 2015.

Alberta Environmental Protection. 1998. The final frontier: protecting landscape and biological diversity within Alberta's boreal forest natural region. Protected Areas Report no. 13. Edmonton, AB: Alberta Environmental Protection.

Archibald, J.H., Beckingham B.D. 1996. Field guide to ecosites of northern Alberta. Edmonton, AB: Canadian Forest Service.

Barbour, S.L., Chanasyk, D., Hendry, J., Leskiw, L., Macyk, T., Mendoza, C., Naeth, A., Nichol, C., O'Kane, M., Purdy, B., Qualizza, C., Quideau, S., Welham, C., 2007. Soil capping research in the Athabasca oil sands region: technology synthesis. Fort McMurray, AB: Syncrude Canada Ltd.

Bhatti, J. S., Vitt, D.H. 2012. Restoration and reclamation of boreal ecosystems: attaining sustainable development. Cambridge: Cambridge University Press, 2012.*eBook Collection (EBSCOhost)*, EBSCO*host.* Accessed on August 18, 2014.

Bonan, G.B., Shugart, H.H. 1989. Environmental factors and ecological processes in boreal forests. Ann. Rev. Ecol. Sys. 20, 1-28.

Bothe, R.A., Abraham, C., 1993. Evaporation and evapotranspiration in Alberta 1986 to 1992 addendum. Surface Water Assessment Branch, Technical Services & Monitoring Division, Water Resources Services. Edmonton, AB: Alberta Environmental Protection.

Boyer, J.S., 1995. Measuring the water status of plants and soils. San Diego, California: Academic Press.

Bréda, N., Huc, R., Granier, A., Dreyer, E., 2006. Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. Ann. For. Sci. 63, 625-644.

Bridge, S.R.J., Johnson, E.A., 2000. Geomorphic principles of terrain organization and vegetation gradients. J. Veg. Sci. 11, 57-70.

Brown, R.L., Naeth, M.A. 2014. Woody debris amendment enhances reclamation after oil sands mining in Alberta, Canada. Restor. Ecol. 22, 40-48.

Burgers, T., 2005. Reclamation of an oil sands tailings facility: vegetation and soil interactions. Master of Science Thesis, Department of Renewable Resources, University of Alberta.

Canadian Boreal Initiative. 2009. Counting Canada's natural capital: assessing the real value of Canada's boreal ecosystems. http://www.borealcanada.ca/documents/BorealBook_CCNC_09_enFINAL.pdf. Accessed on April 27, 2013.

Carey, S.K., 2008. Growing season energy and water exchange from an oil sands overburden reclamation soil cover, Fort McMurray, Alberta, Canada. Hydrol. Process. 22, 2847–2857.

Chin, S., Hogg, E.H., Lieffers, V.J., Huang, S., 2008. Potential effects of climate change on the growth of lodgepole pine across diameter size classes and ecological regions. For. Ecol. Manage. 256, 1692–1703.

Churkina, G., S.W. Running. 1998. Contrasting climate controls on the estimated productivity of global terrestrial biomes. Ecosystems. 1, 206-215

Comeau, P.G., Kimmins, J.P., 1989. Above- and below-ground biomass and production of lodgepole pine on sites with differing soil moisture regimes. Can J. For. Res. 19, 447-454.

Cortini, F., Comeau, P.G., Boateng, J.O., Bedford, L., McClarnon, J., Powelson, A., 2011. Effects of climate on growth of lodgepole pine and white spruce following site preparation and its implications in a changing climate. Can. J. For. Res. 41, 180–194.

Cumulative Environmental Management Association (CEMA), 2006. Land Capability Classification System for Forest Ecosystems in the Oil Sands (3rd Edition).Edmonton, AB: Alberta Environment.

Dang, Q.-L, Margolis, H.A., Coyea, M.R., Sy, M., Collatz, G.J., 1997. Regulation of branch-level gas exchange of boreal trees: roles of shoot water potential and vapor pressure difference. Tree Physiol. 17, 521-535.

Danielson, R.M., Visser, S., Parkinson, D., 1983. Plant growth in four overburden types used in the reclamation of extracted oil sands. Can. J. Soil Sci. 63, 353–361.

Davies, W.J., Zhang, J.H., 1991. Root signals and the regulation of growth and development of plants in drying soil. Ann. Rev. Plant Physiol. Mol. Biol. 42, 55-76.

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

Environment Canada, 2013. Canadian Climate Normal 1971-2000, for Fort McMurray, Alberta. National Climate Data and Information Archive, Government of Canada. http://climate.weather.gc.ca/climate_normals/results_e.html?stnID=2519&prov=&lang=e&dCode=1&dispBack=1&StationName=Fort_McMurray&SearchType=Contains&province=ALL&provBut=&month1=0&month2=12 [Accessed on September 18, 2015].

Environmental Protection and Enhancement Act, 2000. http://environment.alberta.ca/03147.html. Accessed on April 27, 2013.

Farquhar, G.D., Ehleringer, J.R., Hubick, K.T., 1989. Carbon isotope discrimination and photosynthesis. Ann. Rev. Plant Physiol. Mol. Biol. 40, 503–537.

Faubert, J.R., S.K. Carey. 2014. Growing season water balance of wetland reclamation test cells, Fort McMurray, Alberta. Hydro. Proc. 28, 4363–4376.

Finér, L., Helmisaari, H., Lõhmus, K., Majdi, H., Brunner, I., Børja, I., Eldhuset, T., Godbold, D., Grebenc, T., Konôpka, B., Kraigher, H., Möttönen, M., Ohashi, M., Oleksyn, J., Ostonen, I., Uri, V., Vanguelova, E., 2007. Variation in fine root biomass of three European tree species: beech (Fagus sylvatica L.), Norway spruce (Picea abies L. Karst.), and Scots pine (Pinus sylvestris L.). Plant Biosyst. 141, 394-405.

Fisher, R.F., Binkley, D., 2000. Ecology and management of forest soils (3rd Edition). New York, NY: John Wiley & Sons, Inc.

Fung, M.Y.P., Macyk, T.M. 2000. Reclamation of oil sands mining areas. In: R.I. Barmhisel, R.G. Darmody, W.L. Daniels (eds). Reclamation of drastically disturbed lands. Agronomy Monograph No. 41. Amercian Society of Agronomy. Madison, WI. 755-774.

Gilliam, F.S., 2007. The ecological significance of the herbaceous layer in temperate forest ecosystems. Bioscience. 57, 845-858.

Government of Alberta, 1992. Environmental Protection and Enhancement Act (Chapter E-13. 3). Edmonton, AB: Queen’s Printer, Government of Alberta.

Government of Alberta, 1993. Conservation and Reclamation Regulation (AR 115/1993). Edmonton, AB: Queen’s Printer, Government of Alberta.

Government of Alberta. 1963. Surface Reclamation Act (Chapter 64). Edmonton, AB: Queen’s Printer, Government of Alberta.

Government of Alberta. 1969. Public Lands Act (Chapter 91). Edmonton, AB: Queen’s Printer, Government of Alberta.

Government of Alberta. 1973. Land Surface Conservation and Reclamation Act (Chapter 34). Edmonton, AB: Queen’s Printer, Government of Alberta.

Government of Alberta. 1992. Environmental Protection and Enhancement Act (Chapter E-13.3). Edmonton, AB: Queen’s Printer, Government of Alberta.

Government of Alberta. 1993. Conservation and Reclamation Regulation (AR 115/1993). Edmonton, AB: Queen’s Printer, Government of Alberta.

Government of Alberta. 2013. Ministry of Environment and Sustainable Resource Development. Oil sands reclamation. http://www.oilsands.alberta.ca/reclamation.html. Accessed on September 18, 2015.

Gower, S.T., Krankina, O., Olson, R.J., Apps, M., Linder, S., Wang, C., 2001. Net primary production and carbon allocation patterns of boreal forest ecosystems. Ecol. Appl. 11, 1395-1411.

Gregorich, E. G., Carter, M. R., Angers, D. A., Monreal, C. M., Ellert, B. H., 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74, 367-385.

Hahn, A., Quideau, S.A., 2013. Long-term effects of organic amendments on the recovery of plant and soil microbial communities following disturbance in the Canadian boreal forest. Plant Soil. 363:1, 331-344.

Hardie, M.A., Doyle, R.B., Cotching, W.E., Lisson, S., 2012. Subsurface lateral flow in texture-contrast (duplex) soils and catchments with shallow bedrock. Appl. Environ. Soil Sci. 2012, 1-10.

Hardy BBT Limited, 1990. Natural plant invasion into reclaimed oil sands mine sites. Prepared for Reclamation Research Technical Advisory Committee. Edmonton, AB: Alberta Land Conservation. and Reclamation Council.

Hautier, Y., Niklaus, P.A., Hector, A., 2009. Competition for light causes plant biodiversity loss after eutrophication. Science. 324: 636–638.

Havlin, J.L., Beaton, J.D., Tisdale, S.L., Nelson, W.L., 2005. Soil Fertility and Nutrient Management: An Introduction to Nutrient Management. 7th Edition. Upper Saddle River, NJ: Pearson/Prentice Hall.

Hemstock, S.S., Quideau, S.A., Chanasyk, D.S., 2010. Nitrogen availability from peat amendments used in boreal oil sands reclamation. Can. J. Soil Sci. 90, 165-175.

Hillel, D., 1998. Environmental Soil Physics. London, England: Academic Press.

Hobbs, R.J., Salvatore, A., Aronson, J., Baron, J.S., Bridgewater, P., Cramer, V., Epstein, P.R., Ewel, J.J., Klink, C.A., Lugo, A.E., Norton, D., Ojima, D., Richardson, D.M., Sanderson, E.W., Valladares, F., Vila, M., Zamora, R., Zobel, M. 2006. Novel ecosystems: theoretical and management aspects of the new ecological world order. Glob. Ecol. and Biog. 15, 1-7.

Hokkanen, P.J., 2006. Environmental patterns and gradients in the vascular plants and bryophytes of eastern Fennoscandian herb-rich forests. For. Ecol. Manage. 229, 73–87.

Huang, M., Zettl, J.D., Barbour, S.L., Elshorbagy, A., B.C. Si. 2013. The impact of soil moisture availability on forest growth indices for variably layered coarse-textured soils. Ecohydrol. 6, 214-227.

Hudson, B.D., 1994. Soil organic matter and available water capacity. J. Soil Water Conserv. 49, 189-194.

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate change 2007. The science of climate change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. 2007. Cambridge, UK: Cambridge University Press.

Jules, M.J., Sawyer, J.O., Jules, E.S., 2008. Assessing the relationships between stand development and understory vegetation using a 420-year chronosequence. For. Ecol. Manage. 255, 2384–2393.

Jung, K., Duan, M., House, J. and Chang, S.X. 2014. Textural interfaces affected the distribution of roots, water, and nutrients in some reconstructed forest soils in the Athabasca oil sands region. Ecological Engineering. 64, 240-249.

Kessler, S., Barbour, S.L., van Rees, K.C.J.,Dobchuk, B.S. 2010. Salinization of soil over saline-sodic overburden from the oil sands in Alberta. Can. J. Soil Sci. 90, 637-647.

Kruskal, J.B., 1964. Nonmetric multidimensional scaling: a numerical method. Psychometrika. 29, 115-129.

Lamb, E.G., Kembel, S.W., Cahill, J.F., 2009. Shoot, but not root, competition reduces community diversity in experimental mesocosms. J. Ecol. 97, 155–163.

Lambert, M.C., Ung, C.H., Raulier, F., 2005. Canadian national tree aboveground biomass equations. Can. J. For. Res. 35, 1996-2018.

Larney, F.J., Angers, D.A., 2012. The role of organic amendments in soil reclamation: A review. Can.J. Soil Sci. 92, 19-38.

Lazorko, H., Van Rees, K.C.J. 2012. Root distributions of planted Boreal mixedwood species on reclaimed saline–sodic overburden. Water, Air and Soil Pollution. 223, 215-231.

Leatherdale, J., Chanasyk, D. S., Quideau, S. 2012. Soil water regimes of reclaimed upland slopes in the oil sands region of Alberta. Can. J. Soil Sci. 92, 117-129.

Lee, P., Cheng, R. 2009. Bitumen and biocarbon: land use conversions and loss of biological carbon due to bitumen operations in the boreal forests of Alberta, Canada. Edmonton, AB: Global Forest Watch Canada

Li, X., Chang, S.X., Salifu, K.F. 2014. Soil texture and layering effects on water and salt dynamics in the presence of a water table: a review. Env. Rev. 22, 41-50.

Ludlow, M.M., 1980. Adaptive significance of stomatal responses to water stress. *In* Adaptation of plants to water and high temperature stress. Eds. N.C. Turner and P.J. Kramer. New York, NY: John Wiley and Sons.

Lundbald, M., Lindroth, A., 2002. Stand transpiration and sapflow density in relation to weather, soil moisture and stand characteristics. Basic Appl. Ecol. 3, 229–243.

MacDonald, S.E., Quideau, S.A., Landhäusser, S. 2012. Rebuilding boreal forest ecosystems after industrial disturbance. In: J.S. Bhatti, D.H. Vitt (eds). Restoration and Reclamation of Boreal Ecosystems: Attaining Sustainable Development. Cambridge, England: Cambridge University Press.

Mackenzie, D.D., Naeth, M.A. 2010. The role of the forest soil propagule bank in assisted natural recovery after oil sands mining. Restor. Ecol. 18, 418–427.

Mather, P.M., 1976. Computational methods of multivariate analysis in physical geography. London: J. Wiley and Sons.

McCune, B., Grace, J.B., Urban, D.L., 2002. Analysis of Ecological Communities. Gleneden Beach, Oregon, USA: MjM Software.

Meiers, G.P., Barbour, S.L., Qualizza, C.V., Dobchuk,B.S. 2011. Evolution of the hydraulic conductivity of reclamation covers over sodic/saline mining overburden. J. Geotech. Geoenv. Eng. 137, 968-976.

Miller, H.G. 1981. Forest fertilization: some guiding concepts. Forestry. 54, 157-167.

Moskal, T.D. 1999. Moisture characteristics of coarse textured soils and peat: mineral mixes. M.Sc. Thesis. Department of Renewable Resources, University of Albeta. Edmonton, AB. 139 p.

Moskal, T.D., Leskiw, L., Naeth, M.A., Chanasyk, D.S., 2001. Effect of organic carbon (peat) on moisture retention of peat: mineral mixes. Can. J. Soil Sci. 81, 205–211.

Muller, R.N. 2003. Nutrient relations of the herbaceous layer in deciduous forest ecosystems. Pages 15–37 in Gilliam F.S., Roberts M.R., eds. The herbaceous layer in forests of eastern North America. New York: Oxford University Press.

Naeth, M. A., Chanasyk, D. S., Burgers, T. D. 2011. Vegetation and soil water interactions on a tailings sand storage facility in the Athabasca oil sands region of Alberta Canada. Phys. Chem. Earth. 36, 19-30.

Naeth, M.A., S.R. Wilkinson, D.D. Mackenzie, H.A. Archibald and C.B. Powter, 2013. Potential of LFH mineral soil mixes for land reclamation in Alberta. Oil Sands Research and Information Network (ORSIN), University of Alberta, School of Energy and the Environment, Edmonton, Alberta. OSRIN Report No. TR-35. 1-64.

Natural Regions Committee, 2006. Natural Regions and Subregions of Alberta. Compiled by D.J. Downing and W.W. Pettapiece. Pub. No. T/852. Edmonton, AB: Government of Alberta

Nemani, R.R., Keeling, C.D., Hashimoto, H., Jolly, W.M., Piper, S.C., Tucker, C.J., Myneni, R.B., Running, S.W. 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. Science. 300, 1560-1562

Ni, G.-R., Pallardy, S.G., 1992. Stomatal and non-stomatal limitations to net photosynthesis in seedlings of woody angiosperms. Plant Physiol.. 99, 1502-1508.

Nilsson, M.C., Wardle, D.A., 2005. Understory Vegetation as a Forest Ecosystem Driver: Evidence from the Northern Swedish Boreal Forest. Front. Ecol. Environ. 3, 421-428.

Oil Sands Vegetation Reclamation Committee, 1998. Guidelines for reclamation to forest vegetation in the Athabasca oil sands region. Prepared for Alberta Environmental Protection. AEP Report #ESD/LM/99-1.

Osonubi, O., Davies, W.J., 1980. The influence of plant water stress on stomatal control of gas exchange at different levels of atmospheric humidity. Oecologia. 46, 1-6.

Pinno, B.D., Landhäusser, S.M., MacKenzie, D.M., Quideau, S.A., Chow, P.S., 2013. Trembling aspen seedling establishment, growth and response to fertilization on contrasting soils used in oil sands reclamation. Can. J. Soil Sci. 92, 143-151.

Porro, I., 2001. Hydrologic behavior of two engineered barriers following extreme wetting. J. Environ. Qual. 30, 655-667.

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

Purdy, B.G., Macdonald, S.E., 2007. Early successional plant responses to capping treatment on a saline-sodic overburden dump after oil sand mining in soil capping reclamation research. Volume 2: Fact sheet 32, 118-121.

Rowland, S.M, Prescott, C.E., Grayston, S.J., Quideau, S.A., Bradfield, G.E. 2009. Recreating a functioning forest soil in reclaimed oil sands in northern Alberta: an approach for measuring success in ecological restoration. J. Environ. Qual. 38, 1580-1590.

Salinger, S., 2005. Increasing climate variability and change: reducing the vulnerability, Climate Change 70: 1–3.

Saxe, H., Cannell, M.G.R., Johnsen, Ø., Ryan, M.G., Vourlitis, G., 2001. Tree and forest functioning in response to global warming. New Phytol. 149, 369–400.

Schwinning, S., Weiner, J., 1998. Mechanisms determining the degree of size asymmetry in competition among plants. Oecologia. 113, 447–455.

Semchenko, M., Lepik, M., Götzenberger, L., Zobel, K., 2012. Positive effect of shade on plant growth: amelioration of stress or active regulation of growth rate? J. Ecol. 100, 459–466

Shannon, C.E., Wiener, W., 1963. The mathematical theory of communications. Urbana: University of Illinois Press.

Smith, B., Wilson, J.B., 1996. A consumer's guide to evenness indices. Oikos. 76, 70-82.

Smith, R.L., Smith, T.M., 2003. Elements of Ecology. 5th Edition. Benjamin Cummings San Francisco, USA: Benjamin Cummings.

Szwaluk, K.S., Strong, W.L., 2003. Near-surface soil characteristics and understory plants as predictors of Pinus contorta site index in southwestern Alberta, Canada. For. Ecol. Manage. 176, 13-24.

Teskey, R.O., Fites, J.A., Samuelson, L.J., Bongarten, B.C., 1986. Stomatal and non-stomatal limitations to net photosynthesis in *Pinus taeda* L. under different environmental conditions. Tree Physiol. 2, 131-142

Thompson, M.D., Wride, M.C., Kirby, M.E. 1978. Ecological habitat mapping of the Alberta Oil Sands Environmental Research Program (AOSERP) study area: Phase 1. Prep. For the AOSERP by Environmental Consultants Ltd. AOSERP Report 31. 176 p.

Turchenek, L.W., Lindsay, J.D. 1982. Soils inventory of the Alberta oil sands environmental research program study area. Alberta Research Council, Edmonton, AB

Warren, C.R., McGrath, J.F., Adams, M.A., 2001. Water availability and carbon isotope discrimination in conifers. Oecologia. 127, 476–486.

Yarmuch, M.S., 2003. Measurement of soil physical properties to evaluate soil structure quality in reclaimed oil sands soils, Alberta, Canada. Masters of Science Thesis. Department of Renewable Resources. University of Alberta.

Zipper, C.E., Burger, J.A., Skousen, J.G., Angel, P.N., Barton, C.D., Davis, V., Franklin, J.A., 2011. Restoring forests and associated ecosystem services on Appalachian coal surface mines. Environ. Manage. 47, 751-765.