The influence of soil reconstruction materials and targeted fertilization on the regeneration dynamics in boreal upland forest reclamation

By

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Abstract

Soil is an essential component supporting the growth and maintenance of terrestrial ecosystems such as forests, providing anchorage, water, and nutrients. In Canada's boreal forest landscape, surface soils can differ widely in their chemical and physical conditions, ranging from coarse to fine textured mineral soils in the uplands to organic soils in the lowlands. Industrial disturbances in the boreal region require the salvage of surface- and sub-soils from low- and upland areas during open pit mine operations that are used in the reconstruction of soil profiles for forest reclamation. These materials are selectively salvaged and can be arranged in variable layers and thicknesses, which could have profound effects on early forest establishment. For the first project of my thesis, I compared the growth of trembling aspen (*Populus tremuloides* Michx.), jack pine (*Pinus banksiana* Lamb.), and white spruce (*Picea glauca* Moench.) on different reconstructed soil profiles using varying surface soil materials (salvaged lowland peat and upland forest floor material (FFM)), placement depths (10 or 30cm for peat, 10 or 20cm for FFM), and subsoil material types determined by salvage depth (Bm, BC, and C). Early seedling establishment and growth as well as soil and climatic parameters were monitored over a five-year period. Seedling growth was greatest on FFM and appeared to be related to phosphorous availability, while peat as a surface soil reduced growth, likely due to delayed soil warming in the spring and overall cooler soil conditions that potentially limited resource availability. However, the greater water holding capacity of the organic matter in peat provided a benefit for seedling growth that was apparent during water limiting climatic conditions. The underlying subsoil material influenced growth later in establishment when roots occupied the deeper subsoils. Aspen growth was greatest when the subsoil was shallow salvaged and represented a weathered subsoil (Bm) compared to the more deeply salvaged, less weathered subsoils BC and C. Aspen and pine seedlings, with their larger roots systems, may have benefited from small increases in the silt fraction of the subsoils that increased the water holding capacity of these otherwise coarse textured sandy soils. Spruce regeneration responded marginally to soil treatments because of its overall slow growth-strategy and tolerance to resource limitations.

Based on the initial 5-year study, seedlings may have been limited by low phosphorus (P) and potassium (K) availability in the peat and the homogenized subsoil materials, while nitrogen (N) was readily available in the peat coversoil. Broadcast fertilization is a common method used to treat nutrient limitations on reclamation sites, supplying a wide range of nutrients to fulfill the varying requirements that are unique to each tree species; however, operational applications of NPK on organic soils often induce strong responses from unwanted colonizing vegetation, which reduces the nutritional benefits intended for the seedlings and could render the fertilizer application ineffective. A follow-up study was developed to test the use of a broadcast fertilizer application that targets specific nutrient deficiencies in the soil and in each tree species, while simultaneously reducing the response of competing vegetation. Liquid fertilizer was applied to six-year-old seedlings using five treatments in the field: Control (no fertilizer), NPK, PK, P, and K. Seedling growth, foliar nutrients, and vegetation cover as well as environmental parameters were measured over two growing seasons. Aspen responded the strongest to fertilization, particularly in the P treatment, while pine and spruce marginally responded to the NPK treatment; however, growth responses depended on the type of subsoil treatment. All three species had foliar P concentrations below their optimal levels in the Controls, while foliar N concentrations were low for both conifers. The competing vegetation increased in NPK and did not respond to the P, K and the Control treatments, indicating targeted fertilization reduced responses from colonizing competitors. Additional analyses of the soil conditions (e.g. pH, cation sorption, water availability, temperature) suggest that other factors were more limiting to the trees during the study, which reduced their responses to the fertilizer additions. Results from this thesis demonstrate how different strategies used for soil reconstruction and targeted fertilization can affect the

performance of forest regeneration in post-mine areas, and boreal forest species responses may vary according to their ecological adaptations and the site conditions.

Preface

The following thesis is an original work, and the data from Chapter 2 was collected and analyzed by both Jana Bockstette (first three years of study; Bockstette, 2018)) and Shauna Stack (last two years), while data from Chapter 3 was collected and analyzed by Shauna Stack only. No part of this thesis has been previously published.

The first project pertaining to the 'Aurora Soil Capping Study' over the first five years after planting was part of a research collaborative between Syncrude Canada Ltd. and researchers of the University of Alberta, and the manuscript for this project has since been submitted to the journal called Ecological Engineering for publication in June 2019. Seedling height and root collar diameter were collected by Jana Bockstette in the first three years of the study and the last two years were collected by Shauna Stack. Biomass and initial seedling characteristics were collected and analyzed by Jana Bockstette. Meteorological and soil physical conditions (i.e. soil temperature and soil water content) were collected by O'Kane Consultants Ltd. over all five years and statistically analyzed by Shauna Stack. Soil chemical properties (i.e. plant available nutrients, sodium adsorption ratio, electrical conductivity, pH) were collected by Northwind Land Resources Inc. and statistically analyzed by Shauna Stack. Results from Chapter 2 ("Surface and subsoil reconstruction materials influence regeneration dynamics in boreal upland forest reclamation") have been presented in an oral presentation at the 1) 2018 Oil Sands Innovation Summit in Calgary, Alberta, Canada and 2) 2018 CLRA/ACRSD National Conference in Miramichi, New Brunswick, Canada.

The second project pertaining to 'targeted fertilizer application at the Aurora Soil Capping Study' was part of the same research collaborative as the first project. Experimental design and measurements regarding seedling height and root collar diameter, foliar nutrient concentrations, vegetation cover, and soil chemical properties (i.e. plant available nutrients, sodium adsorption ratio, electrical conductivity, pH) were developed, collected, and statistically analyzed by Shauna Stack. Meteorological and soil physical conditions (i.e. soil temperature and soil water content) were collected by O'Kane Consultants Ltd. and statistically analyzed by Shauna Stack. Results from Chapter 3 ("Species specific responses to targeted fertilizer application on reconstructed soils in a reclaimed upland area") have been presented in an oral presentation at 1) the CLRA Lunch and Learn in April 2019 in Edmonton, Alberta, Canada, and 2) as a poster presentation at the 2019 Oil Sands Innovation Summit in Calgary, Alberta, Canada.

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Chapter 1: Soil Reconstruction and Re-forestation: Upland Reclamation in the Athabasca Oil Sands Region

1.1 A Diverse Ecosystem Under Several Disturbances: The Boreal Forest

Forests are an integral part of many terrestrial environments, covering approximately 30% of the global land surface (Bonan, 2008). These forested ecosystems are important drivers of climate, nutrient, and water cycles across the globe (Woodward, 1987), while at a smaller scale, they foster biodiversity through the refuge, habitat, and resources they provide (Hooper et al., 2005; Mori et al., 2017). Humankind has greatly benefited from these forests given the ecological, economical, social, and aesthetic services they provide, using them as sources of food, clean and filtered water, medicines, and raw products, as well as areas for recreational and spiritual activities (Hassan et al, 2005). The boreal forest biome is the northern most forested area that covers 28% of Canada and parts of northern Europe and Asia (Bonan & Shugart, 1989; Brandt, 2009). Mixtures of cold-tolerant coniferous and deciduous tree species dominate the Canadian boreal landscape, and these species are specially adapted to the moderately warm and moist summers and the extended periods of dry cold winters associated with this region. In Alberta, Canada, over half of the province is covered by the boreal forest (Alberta Wilderness Association, 2019), encompassing a vast expanse of gently undulating plains and unique upland and lowland ecosystems that support water filtration and storage, nutrient cycling processes, carbon storage, and renewable and non-renewable resources (Brandt et al., 2013; Natural Regions Committee, 2006).

The establishment of forest vegetation is largely governed by the soils that vary across the landscape (Beckingham & Archibald, 1996), and the type of soils that form are influenced by the changing climate, topography, and underlying parent geological materials (Ordoñez et al., 2009; Stockmann et al., 2017). Upland areas in the Alberta boreal forest are the remnants of glacial depositional processes that occurred during the last glaciation, and these features are often composed of fine textured lacustrine deposits, medium textured tills, or coarse textured fluvial and eolian sands (Turchenek & Lindsay, 1982). These sediments were transformed under weathering pressures to form unique upland soils such as Brunisols (Smith et al., 2011) on the coarse sediments and Gray Luvisols (Lavkulich & Arocena, 2011) where clay contents are higher. Forest stands are commonly dominated by early successional trembling aspen (*Populus tremuloides* Michx.), late successional white spruce (*Picea glauca* (Moench) Voss.), or a combination of the two species on the fine to medium textured soils, while jack pine (*Pinus banksiana* Lamb.) is commonly found on coarser soils. In forested lowland areas, soil conditions are generally wet and poorly drained, forming deep organic deposits, and if these lowland soils are treed, they are commonly dominated by mixed stands of black spruce (*Picea mariana* Mill.) and tamarack (*Larix laricina* (Du Roi) K. Koch) (Beckingham & Archibald, 1996; Natural Regions Committee, 2006).

Natural disturbances, such as wildfire, extreme weather events, and insect or disease outbreaks (Gutschick & BassiriRad, 2003; Mattson & Addy, 1975; Weber & Flannigan, 1997), contribute additional complexities to the boreal by continuously changing the composition and structure, creating a mosaic of forested ecosystems across the landscape (Gunderson, 2000; Peterson et al., 1998). The strength and impact of these disturbances are intricately connected and largely dependent on the climate (Flemming & Volney, 1995; Weber & Flannigan, 1997), and with the rise of global temperatures and changes in precipitation towards drier conditions, the susceptibility of forests to natural disturbance events of a higher intensity and frequency than is historically normal may increase and drastically change the vegetation dynamics of the boreal forest (Walther et al., 2002). Human related activities are a recent addition to the set of disturbances that affect the boreal forest, and the magnitude and extent of these activities continue to intensify as the global demand for resources increase (Maynard et al., 2014; Vitousek et al., 1997). The Canadian boreal is rich in non-renewable resources and raw products such as timber, metal ores, and petroleum materials (Government of Canada, 2019a), and commercial and industrial activity has expanded in the region as extraction and demand for these products increased over the last century (Schneider et al., 2003).

Northern Alberta has the third largest oil reserve in the world, and 20% of this resource is recoverable by surface mining (Government of Canada, 2019a). The increasing use of surface mining has contributed to the growing need for forest reclamation and restoration across the world (World Resources Institute, 2019). However, surface mining introduces a unique form of disturbance that has few natural analogues for comparison (Doley & Audet, 2013; Hiers et al., 2012), and with a changing climate, the recovery of mine areas often result in novel ecosystems that greatly differ from the surrounding undisturbed areas (Hobbs et al., 2009). Unlike natural disturbances that generally affect the above and below ground vegetation and potentially the organic layers of the soil (Hart & Chen, 2008; Norris et al., 2009), surface mining is not isolated to the surface of the forest, extending across the entire soil profile, the underlying parent geological material, and the overall landscape, which abruptly halts the hydrological, nutrient, and physical processes and cycles within the forest soils (Johnson & Miyanishi, 2008; Zipper et al., 2013). After the active mining phase is complete, the altered landscape and residual materials often resemble the physical and chemical characteristics of a pre-weathered state, which can be limiting in the essential properties required for plant growth such as nutrient and water availability, soil organic matter, soil microorganisms, and a propagule bank (Duan et al., 2015; Li & Fung, 1998; Mackenzie & Naeth, 2010; Quideau et al., 2013; Rowland et al., 2009). Therefore, these post-mining environments require additional human intervention to assist in the recovery and development of functioning forests within a reasonable amount of time (Cumulative Environmental Mangement Association, 2009).

1.2 Landform and Soil Reconstruction in Mined Areas

Since the first enactment of the Surface Reclamation Act in 1963, industrial land conservation and reclamation in Alberta has evolved from a focus on safety hazards and the clearing of surface debris to an ecological perspective that encompasses the re-establishment of biodiversity and ecosystem function (Ciccarese et al., 2012; Powter et al., 2012; Rey-Benayas et al., 2009). Current legislation from the Government of Alberta (2019) requires mine operators to 'reclaim the land so that the reclaimed soils and landforms are capable of supporting a self-sustaining, locally common boreal forest' that can integrate with the surrounding area. Ongoing collaborations between industry, government, and academia have and continue to address challenges in reclamation and contribute to the development of best prescriptions and practices.

The first step in mine reclamation is landscape re-construction within the excavated area, and in Alberta's boreal, this includes the construction of topographically high landforms that are connected to depressions in the landscape where wetlands, end pit lakes, and other waterways are established (Devito et al., 2012; Elshorbagy et al., 2005). At the beginning of the active mine phase, the soil horizons and underlying parent materials are excavated and stockpiled for later use or immediately used on active reclamation sites. The parent materials, commonly called the overburden, are generally dumped into large piles that are re-contoured and incorporated into the closure landscape as permanent upland features. Depending on the type of overburden material used, there may be issues with low water holding capacity and nutrient availability that can limit the establishment and growth of vegetation (Jung et al., 2014; MacKenzie & Quideau, 2010; Ojekanmi & Chang, 2014; Rowland et al., 2009; Wang et al., 2016); therefore, salvaged soil materials are used to cover the overburden and act as a suitable rooting medium for future forest development.

The reconstruction of a suitable rooting medium can be challenging given its essential role in supporting the development and maintenance of forest ecosystems, which include long-lived plants like trees (Rodrigue & Burger, 2004; Zipper et al., 2012). Soil materials used to construct the rooting medium are salvaged within the mine footprint and either placed directly on a reclaimed site or stockpiled for later use (Mackenzie & Naeth, 2010; Naeth et al., 2013). The establishment and growth of planted and naturally regenerated vegetation will require an ample and constant supply of resources during the initial years following reclamation (Groninger et al., 2007), therefore the materials used to create the soil cover must be able to support these demands in order to maintain the trajectory towards a successful recovery (Bussler et al., 2010; Howell et al., 2016). One method used for soil re-construction is to emulate the horizons of natural soils by selectively salvaging distinct horizons and placing them on the reclamation site in separate layers, which partially retains the heterogeneity of textural and nutrient layers from the original soil profile (Hargis & Redente, 1984; Naeth et al., 2012); however, this method is often difficult to facilitate with the large machinery used in the excavation and handling of these materials, which are required when reclaiming at the large operational scales associated with surface mines. Therefore, an alternative method that is more economical and feasible for mine operators is to salvage soils in a single lift and place the materials on site as a blended and homogenous soil profile, which often reduces the number of horizons, their sequences, and thicknesses (Naeth et al., 2013).

1.3 Soil Cover Prescriptions and Design for Forest Reconstruction

Compared to landscapes reconstructed for agricultural use, upland forest reconstruction often requires a thicker soil cover to support the deep-rooted tree species that are planted in these areas (Gale & Grigal, 1987; Stone & Kalisz, 1991; Strong & La Roi, 1983a). The ideal soil materials for upland forest reclamation are salvaged from soils developed on natural upland sites (Naeth et al., 2013; Skousen et al., 2011), where the upper L-F-H layers and part of the A horizon would serve as the topsoil layer (coversoil) and the underlying B and C horizons would provide the underlying subsoil layers. Coversoil materials salvaged from natural upland forest sites are generally termed forest floor materials (FFM), and they promote the development of soil microbial communities (Hahn & Quideau, 2013; McMillan et al., 2007) that are similar to natural upland areas, provide a propagule bank of native upland plant species (Grant et al., 2007; Jones & Landhäusser, 2018; Macdonald et al., 2015a), and generally have a high availability of essential nutrients like phosphorus and potassium for supporting rapid vegetation growth (Brown & Naeth, 2014; Howell et al., 2016; Rowland et al., 2009). However, FFM salvaged from coarse-textured soils like Brunisols will likely have a low water holding capacity, especially when the underlying subsoils are also coarse textured (Huang et al., 2013; Zettl et al., 2011), and this may limit water availability during dry years and slow the growth of the developing vegetation (Fageria, 2013; Kreuzwieser & Gessler, 2010). The FFM required for coversoil reconstruction is often found in thin layers on natural upland sites, and these sites are less abundant than lowland areas in the region, resulting in a shortage of this material for use in upland reclamation.

An alternative option that has been used for coversoil reconstruction are organic soil materials (i.e. peat) salvaged from wetlands that contain several meters of peat overlying mineral soils, making this material highly abundant for reclamation purposes (Macdonald et al., 2015b; Mackenzie & Naeth, 2010). Peat materials are deemed suitable given the higher content of organic matter associated with organic soils (Ojekanmi & Chang, 2014), which provides a large source of undecomposed material to initiate nutrient cycling processes, particularly N mineralization (Hemstock et al., 2009; MacKenzie & Quideau, 2012). Furthermore, the porous structure of the organic matter that is often composed of *Sphagnum* moss can absorb and hold large volumes of water for plant uptake (Rezanezhad et al., 2010).

There are many types of peat that may be used in reclamation, and depending on its origin, chemistry and physical properties (Turetsky et al., 2000), the use of peat as a coversoil can pose challenges when placed on upland sites. Soil temperature limitations may arise if the physical properties of the peat material create insulative conditions that reduce temperatures in the root zone. Zhao and Si (2019) reported that the thermal conductivity of a peat-mineral mix decreased as the peat:mineral ratio increased, highlighting the significant impact that organic matter can have on soil temperature conditions and potentially on tree growth. Most boreal tree species are sensitive to soil temperatures below 5°C, at which point the metabolic activity and overall uptake of water and nutrients are slowed within the root zone, inhibiting other physiological processes that drive growth within the trees (Landhäusser et al., 2001, 2003; Wan et al., 1999; Wolken et al., 2010). Lower nutrient availability in the peat materials has also been reported for macronutrients like phosphorus and potassium (Howell & MacKenzie, 2017; Quideau et al., 2017) and potentially some micronutrients like copper (Dietrich et al., 2017), which can significantly lower the growth rates of planted trees and affect the composition of understory communities (Pinno & Errington, 2015; Pinno & Hawkes, 2015).

As the understanding of peat and its use in upland reclamation has improved, several methods and applications have been developed to help ameliorate the nutrient and temperature limitations associated with peat coversoil materials. When treating the soil temperature limitations associated with thick placements of peat, a greater amount of mineral soil is incorporated to form a peat-mineral mix to increase the thermal conductivity of the material while retaining the benefits of a high-water holding capacity (Moskal et al., 2001). The placement of underlying subsoil layers that are salvaged from an upland site can further improve the temperature conditions in the peat coversoil layer by promoting drainage and reducing the chances of over-saturation that could exacerbate the cool soil temperatures; generally, thicker placements of subsoil materials have been reported to improve water movement within the soil cover rather than shallow placements (Huang et al., 2015; Jackson et al., 2011). The type of subsoil material used can also improve the nutrient availability that are lacking in the peat coversoil. Incorporating weathered subsoil materials can increase concentrations of inorganic nutrients, especially when the subsoil is selectively salvaged and placed on site as a layer underneath the coversoil (Rowland et al., 2009; Skousen et al., 2011). However, as mentioned in Section 1.2, selective salvage is often less feasible and costly considering the large areas requiring reclamation and the heavy machinery used; therefore, the subsoil horizons are often deeply salvaged in a single lift, mixing the upper weathered B horizons with the less weathered C horizons from below to form a homogenous material that has a diluted nutrient concentration compared to the selectively salvaged materials (Naeth et al., 2013).

1.4 Revegetation Challenges in Reclaimed Uplands

Following soil placement, upland areas are often planted with mixtures of tree and understorey species, which accelerates the establishment and growth of the targeted forest cover, and reduces the risks associated with other methods like natural regeneration that can result in slower establishment and a less diverse vegetation cover (Davis et al., 2012). Planting a mixture of species with different life strategies can improve the resiliency of the area to stressors like pests and disease (Thompson et al., 2009) and increase forest productivity and biodiversity through resource partitioning and the provision of varying habitats (Macdonald et al., 2015b). Despite the benefits of planting trees directly on site, the establishment and subsequent growth of the seedlings will be dictated by the conditions of the reconstructed soil cover (Sheoran et al., 2010), particularly in the upper soil layers where the seedling root plugs are isolated until their roots expand and reach the lower soil layers (Hahn & Quideau, 2013; House, 2015; Sorenson et al., 2011). If these soils are lacking in one or more resources, the growth rates of the seedlings will likely decrease (Knecht & Göransson, 2004; Sinclair et al., 1997), which postpones canopy closure further into the future. This is particularly challenging when coarse-texture materials are used to reclaim upland features, where the large pore spaces in these soils are quickly drained following precipitation events, decreasing the availability of stored water and dissolved nutrients required to support the planted seedlings (Huang et al., 2013; Kljun et al., 2006; Zettl et al., 2011).

Despite these planting strategies, the soil covers remain predominately bare during the initial years when vegetation is establishing and growing, and these bare substrates may be exposed to the recruitment of less desirable and non-native species. In many cases, the seeds of these colonizing species are wind dispersed and can widely establish across a recently reclaimed area, creating strong competition with the planted and native vegetation for resources, which introduces additional stressors in an already challenging environment (Carter, 2002; Franklin et al., 2012; Fung & Macyk, 2000; Pokharel et al., 2017). Incorporating early-successional tree species into the planting mixture is important because these fast growing species can create a continuous canopy cover in a relatively short period of time (Parrotta et al. , 1997), after which point the conditions are set for the establishment of desirable understorey vegetation that can out-compete the shade-intolerant and invasive species (Chen et al., 1998; Macdonald et al., 2015a). Cover soil materials that were originally stockpiled may introduce additional challenges when developing a desirable understorey, particularly if the soil is stored for long periods of time, resulting in the deterioration of the propagule bank and microbial community (Mackenzie & Naeth, 2010; Naeth et al., 2013). Competition can also arise from the type of tree species planted across a site, and it is important to consider the life strategies and resource requirements, planting location, and climate when selecting the target species to ensure they are suited to the site conditions and will not out-compete each other (Davis et al., 2012).

1.5 Nutrient Amendments for Reconstructed Soils

In cases where the type of peat and deeply salvaged subsoils used for soil reconstruction are limiting in essential nutrients, additional interventions using nutrient amendments can be used to create the optimal conditions for forest establishment and growth, and these amendments can be either organic or inorganic. Organic amendments such as livestock by-products, biosolids, pulp and paper mill by-products, wood residuals, and crop residues have been used in reclaimed soils to improve the biological, chemical, and physical properties of the mine soils (Bulmer, 2000; Hanay et al., 2004; Larney & Angers, 2012; Pichtel et al., 2010). Biochar, also known as pyrogenic carbon, has recently gained attention for its use as an organic amendment, particularly in the boreal region where wildfire is a natural driver of change (MacKenzie et al., 2014). Native forest soils naturally contain layers of partially combusted organic matter, where it improves nutrient availability given its high surface area and ability to readily adsorb organic and inorganic compounds. Given the different qualities of organic matter held in peat compared to upland soils, it is believed the additions of pyrogenic carbon can help align the decomposition process, nutrient availability, and microbial community of peat materials with that of natural upland soils. Dietrich and MacKenzie (2018) demonstrated this effect by combining biochar with a peat-mineral-mix, which significantly improved the K availability and growth of trembling aspen seedlings. However, biochar is a relatively new product that is costly to produce, and additional research is required to understand the appropriate application rates for different soil types (Saifullah et al., 2018; Solaiman & Anawar, 2015).

For many years, applications of inorganic fertilizer has been the most common method used for nutrient amelioration in both reclamation and forestry (Allen, 1987). Nitrogen is generally the most limiting nutrient in terrestrial ecosystems due to its slow mineralization from organic matter (Näsholm et al., 1998; Vitousek & Howarth, 1991), and as a result, the application of nitrate and ammonium fertilizers have been shown to greatly improve the growth rates of boreal tree seedlings (Siemens & Zwiazek, 2013; Weetman et al., 1985). Peat materials used in reclamation often have a higher nitrate availability compared to upland salvaged soils (Howell et al., 2016; MacKenzie & Quideau, 2012; Ojekanmi & Chang, 2014), but the nitrogen in these peat coversoils may still be limiting in the form of ammonium to some conifer species that are sensitive to this nutrient (Duan et al., 2015; Kronzucker et al., 1997). Phosphorus is another macronutrient that is often limiting in peat materials (Howell et al., 2016; Quideau et al., 2017), particularly for deciduous species like trembling aspen that require large amounts of phosphorus to support their rapid growth rates during their establishment phase (Chapin III et al., 1986; Liang & Chang, 2004; van den Driessche et al., 2003, 2005). The chemical properties of peat can greatly vary depending on the salvage location (Ojekanmi & Chang, 2014; Turetsky et al., 2000), and it is for this reason that pH should be considered when using fertilizer to treat nutrient limitations in peat coversoils, because it can greatly influence the availability of the applied nutrients and the uptake ability of the roots (Böhlenius et al., 2016; DesRochers et al., 2003; Zhang & Zwiazek, 2016).

A common challenge associated with fertilization of bare soil materials is the strong response from the colonizing vegetation present on site. The most economical and practical approach when fertilizing is to use a broadcast application of nutrients that can meet the nutritional requirements for all species of seedlings; however, these nutrients are also made available to any germinants or established vegetation that can readily compete for this resource (Pinno & Errington, 2015). Strong vegetation responses are typically associated with the addition of fertilizers containing nitrogen, and this is particularly the case for non-native species that typically migrate onto reclaimed sites by the wind (Audet et al., 2015; Crompton & Bassett, 1985); after they establish, these species can aggressively compete for the applied nutrients and reduce the nutrient benefits intended for the planted seedlings (Pinno & Errington, 2015; van den Driessche et al., 2005). One method used to reduce the strong response of unwanted vegetation is weed control, where pesticides or mechanical methods are used to reduce the understory cover, and it has been reported to improve the growth and nutrient translocation of planted seedlings early in their establishment and later during maturity (Pokharel et al., 2017; Sutton, 1995). Another option is to use controlled-release fertilizers rather than immediate-release, and to place the fertilizer in a contained area near the root plug of the planted seedlings where the nutrients are slowly released over time and are unavailable to the surrounding colonizing vegetation (Sloan & Jacobs, 2013). Others have developed an entirely different method to improve tree establishment after planting without fertilizing in the field by nutrient loading target upland seedlings like trembling aspen (Schott et al., 2016) and white spruce (Pokharel et al., 2017) with a specific fertilizer regimen during the nursery phase to increase the size of their root systems, which has proven to increase the ability of these species to compete with thick vegetation covers following planting. One method that has not been tested in a reclamation setting is the use of individual nutrients such as phosphorous or potassium, rather than a broad spectrum fertilizer, to amend nutrient limitations in the reclaimed soils and the targeted seedlings, which could possibly reduce the strong response of colonizing vegetation that is commonly associated with the application of nutrients in combination.

1.6 Objectives

The overall objective of this thesis was to assess the establishment and growth of three upland boreal tree species on a reclaimed upland site following surface mining, specifically assessing seedling performance on two different reconstructed coversoils (lowland peat and an upland sandy soil) that differed in their placement depths and three upland subsoil materials salvaged with increasing depth, as well as the impact of a targeted fertilizer amendment on trees grown in nutrient limited soil materials. In both studies, the meteorology and physical and chemical properties of the reconstructed soil materials were also assessed. The knowledge gained from this study will be useful in the development of operational criteria for reconstructing capping soils used in boreal forest reclamation, while informing on the impacts of soil prescription on afforestation and furthering the development of functional and sustainable forest ecosystems.

In Chapter 2 of this thesis, three tree species (trembling aspen (*Populus tremuloides* Michx.), jack pine (*Pinus banksiana* Lamb.), and white spruce (*Picea glauca* Moench.) were assessed over a five year period following planting for their growth responses to 1) two reconstructed coversoil materials that included a peat material salvaged from a lowland area and an upland salvaged forest floor material (L-F-H layers and part of the A horizon), 2), the placement depths of these coversoil materials where peat was compared between 10cm and 30cm and 10cm and 20cm for FFM, and 3) three different subsoil materials salvaged with increasing depth from a natural upland site, which included a selectively salvaged subsoil Bm and two homogenized materials termed subsoil BC and subsoil C. Over the same time period, meteorological and soil nutrient, moisture, and temperature data was collected to assess the interaction between the three tree species and the chemical and physical properties of the reconstructed soil materials.

Chapter 3 discusses a follow-up study developed from the results of the second chapter. Reconstructed soil materials that produced the slowest growth rates over the initial five-year period (i.e. peat coversoil material placed over deeply salvaged and homogenous subsoils) were correlated with limitations in essential nutrients (i.e. phosphorus and potassium), and these soils were selected for treatment by fertilizer application to ameliorate the nutrient limitations in the soils. A targeted fertilizer application of individual nutrients (i.e. NPK, PK, P, K, and a Control) was tested for its ability to supplement the nutrient limitations in the soil materials and in the tree species being targeted, while possibly reducing the competitive response of colonizing vegetation that often renders fertilization ineffective.

Chapter 2: Surface and subsoil reconstruction materials influence regeneration dynamics in boreal upland forest reclamation

2.1 Introduction

Above- and belowground vertical structure, such as the layering of tree canopies and soil horizons, are essential elements in forest ecosystem functioning, creating conditions that drive forest diversity and biogeochemical and hydrological cycling between soils and plants (Hart & Chen, 2008; Macdonald & Fenniak, 2007). Anthropogenic disturbances, such as surface or open pit mining, often result in the disruption or loss of these relationships and functions (Macdonald et al., 2015b; Pickell et al., 2013), since it requires the complete removal of the existing vegetation and soil materials (topsoil, subsoil and geological overburden material) to access and extract the resource (Cumulative Environmental Management Association, 2009; Rowland et al., 2009). After mining and as part of the reclamation and restoration process, the topography, including soils and vegetation, of an entire landscape need to be reconstructed (Zipper et al., 2013). Given the scale of most surface mines, there are no natural disturbance analogues that could provide recovery trajectories to serve as a comparison; therefore, the reclamation and re-establishment of forests and their functional processes require novel approaches to assist in their recovery (Hiers et al., 2012; Hobbs et al., 2009; Jacobs et al., 2015).

A priority in forest reclamation is the rapid establishment of tree canopy cover (Macdonald et al. 2015b); however, the reconstruction of the landscape (topography) and the growing medium (surficial soil) from salvaged overburden and other soil materials plays a crucial part in the success of recovery. Soil reconstruction is a major challenge in forest land reclamation because forest soils must sustain deep-rooted and long-lived plants (i.e. trees) over decades or centuries, during which these ecosystems are exposed to a wide range of climatic conditions, disturbances, and other biotic and abiotic stresses. Although it is impossible to exactly recreate the distinct soil horizons and their unique characteristics that can be found in natural soils, reclamation practices can attempt to emulate some of the same characteristics that might provide short- and long-term ecosystem benefits (Burton & Macdonald, 2011; Naeth et al., 2012; Zipper et al., 2011, 2012).

The initial step in forest reclamation is the reconstruction of geo-technically stable landforms using overburden (OB) material that was originally geologically situated above the resource and below the parent material of the surface soils (Toy & Chuse, 2005). The chemical and physical characteristics of the OB influence its reclamation capability, or conversely, its limitations in the mine closure landscape. The subsequent addition of a reconstructed soil cover, comprised of salvaged coversoil and subsoil materials, is a practical and effective strategy to mitigate potential limitations or environmental risks of unsuitable OB substrates (Macdonald et al., 2012b; Zipper et al., 2012). Creating a suitable soil cover design with appropriate soil material horizons and thicknesses can help minimize the economic and ecological risk of failure of reclamation areas (Cumulative Environmental Mangement Association, 2009; Macdonald et al. 2015b). Once the landforms are built, salvaged subsoil materials are placed on top of the OB and covered with salvaged topsoil (coversoil) materials (Oil Sands Vegetation Reclamation Committee, 1998). The coversoil material and the nutrients and soil organic material (SOM) contained within play an important role in short-term nutrient cycling and water infiltration and storage (Berg & Laskowski, 2005; Zhuang et al., 2008). In contrast, the shallower subsoil horizons (e.g. weathered B-horizon) are typically characterized by lower SOM, microbial activity, and nutrient content than the topsoil material, but may have higher availability of less mobile nutrients, such as phosphorous, than the deeper parent material (C-horizon) (Ojekanmi & Chang, 2014; Wolken et al. 2010). Deeper C-horizon subsoils can, however, support the essential long-term availability of mineral nutrients through weathering, while also providing structural support for deep-rooted plants and long-term water storage (Smith et al., 2011; Strong & Roi, 1985). Boreal tree species show a range of rooting strategies that are a reflection of their natural growing conditions (Strong & La Roi, 1983b). Some species are adapted to deep soil profiles and low water tables that can be found in upland areas, particularly on coarse textured soils, and have evolved to allocate a larger proportion of their growth to the root system, which expands their access to resources (Stone & Kalisz, 1991; Strong & La Roi, 1983a).

In the boreal forest region of northern Alberta, the areas that are predominantly disturbed by open pit mining are dominated by lowland forests that have organic soils composed largely of peat rather than mineral soils (Solodzuk et al., 1982). The use of salvaged upland forest floor material (i.e. organic L, F, H horizons and the upper mineral A horizon) is preferred for upland forest reclamation; due to its greater availability, however, peat salvaged from these lowland forests (i.e. treed bogs and fens) are commonly used as a soil cover in upland forest reclamation (Fung & Macyk, 2000; Rowland et al., 2009; Ojekanmi & Chang, 2014; Pinno et al., 2012a). The predominant use of peat can introduce challenges in upland reclaimed areas, which are dry and differ widely in their forest community and productivity.

The Aurora Soil Capping Study (ASCS) was established in 2011 to assess the impact of different reconstructed soil covers on early upland tree seedling and forest establishment at an operational scale. The objective of this study was to assess early establishment and growth of three boreal tree species (trembling aspen (*Populus tremuloides* Michx.), jack pine (*Pinus* *banksiana* Lamb.), and white spruce (*Picea glauca* Moench.)) in response to coversoil material type and its depth and the underlying subsoil material, and relate these responses to the soil physical (i.e. soil temperature, water content, texture) and chemical (i.e. nutrient availability, pH, electrical conductivity, sodium adsorption ratio) properties of these capping materials.

2.2 Methodology

2.2.1 Study Site

The ASCS site, a large-scale (36ha) reclamation experiment, is located in the Syncrude Aurora North-Mine lease, about 80km north of Fort McMurray, Alberta, Canada (57°20'N, 111°31'W). The site is located within the central mixedwood natural subregion, which is characterized by a rolling terrain of upland and lowland forests. Mixed stands of trembling aspen and white spruce are often found growing on Luvisolic soils while pure jack pine stands are found on Brunisolic soils in the upland areas (Natural Regions Committee, 2006). Lowland bogs and fens are dominated by black spruce (*Picea mariana* Mill.) and tamarack (*Larix laricina* (Du Roi) K. Koch) stands that have developed on poorly drained organic soils (Natural Regions Committee, 2006). Growing season (May-September) climate normals (1981-2010) for the area had an average daily temperature of 13.4°C and total precipitation of 284.3mm (Government of Canada, 2019b). At the ASCS, average daily temperatures during the first five growing seasons of the study (beginning 10 days after first daily average temperature >5°C and ending at first frost) were 15.5°C (2012), 16.9°C (2013), 15.1°C (2014), 14.5°C (2015), and 15.2°C (2016). Total growing season precipitation was 253.2mm (2012), 266.9mm (2013), 315.4mm (2014), 209.1mm (2015), and 342.8mm (2016).

2.2.2 Experimental Design

The reclamation site is on a relatively flat plateau with a gentle slope (< 5%) and an east – west aspect at an elevation of 350m on an overburden (OB) dump. The dump was constructed using lean oil sand (LOS) OB material which has a sandy loam texture, neutral pH, and low bitumen concentration (average 2.7%). The grading of the OB on the ASCS surface landform was completed in 2011 and soil materials were placed prior to the spring of 2012. Thirteen different soil cover treatments were randomly assigned across the study site, and each soil treatment was structured into 1-ha cells and replicated three times within the split-plot factorial design, with soil treatment as the plot effect and tree planting treatment as the split effect (Figure A-1). For this study, we used six of the soil treatments; they varied in the type and thickness of coversoil material placed over three differing subsoil layers (Figure 2-1).

Two coversoil materials were used in this study. Peat coversoil was salvaged to mineral soil contact (approximately 3-4m) from a lowland black spruce and tamarack-dominated forest. The second coversoil was a forest floor material (FFM) that was salvaged to a maximum depth of 15cm in a jack pine-dominated upland forest, which was underlain by a coarse-textured (predominately loamy sand), Brunisolic soil. At that salvage depth the organic litter layers (L,F,H) and the underlying mineral A horizon and potentially a portion of the B horizon were included in the coversoil material. All coversoils were salvaged and directly placed on the reclamation site without storing the material in stockpiles. Three different subsoil materials (depending on salvage depth) were salvaged near the Brunisolic upland soils; therefore, all subsoils shared the same glaciofluvial geologic parent material. The Subsoil Bm was salvaged between a soil depth of 15 and 50cm, the Subsoil BC material was salvaged between 50 and 100cm, which included the B and underlying C horizons, and the Subsoil C material was salvaged from a depth of 15 to 250cm, which included the Bm, B, and C horizons. The Bm and BC subsoil materials were salvaged three years prior to their placement and stockpiled while the subsoil C material was salvaged and directly placed. Depending on the assigned soil treatment, Peat coversoil was placed at a target thickness of 10 or 30cm and the FFM coversoil was placed at 10 or 20cm. Coversoils were underlain by different subsoil material types (i.e. Subsoils Bm, BC, or C) in a range of configurations. The total depth of the soil cover placed over the OB was 150cm for all soil treatments used in this study (Figure 2-1).

Within each soil treatment cell, four tree plots (25m × 25m) were established (Figure A-1). Three of the tree plots were planted with a single tree species of either trembling aspen, jack pine, or white spruce, while the fourth tree plot was planted with an even mixture of all three species. All seedling stock was grown from local seed sources and produced at a commercial nursery (Smoky Lake Forest Nursery Ltd.) under operational protocols described in Landhäusser et al. (2012a). Aspen and spruce seedlings were sown into 615A StyroblockTM (Beaver Plastics Ltd, Acheson, Alberta), while pine seedlings were sown into 412A StyroblockTM (Beaver Plastics Ltd, Acheson, Alberta). All seedlings were planted as one-year-old seedlings. Aspen seedlings averaged 30cm tall, spruce 29cm, and pine 18cm at time of planting (Table B-1). Seedlings were hand-planted in June 2012 at a regular 1m × 1m spacing (equivalent to 10,000 stems per hectare (sph)). The areas outside the tree plots in each soil treatment cell were planted with a mixture of the same tree species at a density of approximately 2,000sph, as well as three native shrub species: pincherry (*Prunus pensylvanica* L.f.), green alder (*Alnus crispa* Chaix.), and saskatoon (*Amelanchier alnifolia* (Nutt.) Nutt. ex M. Roem.) at a density of about 800sph. For this study, we only present data from tree plots that were planted with a single species at 10,000sph.

Seedling growth from 2012-2016, total height of seedlings in 2016, and their relative growth (i.e. growth from 2012-2016 relative to initial 2012 height for among species comparisons) were compared in response to:

(1) Coversoil material type (FFM and Peat) where soil cover treatments 1 and 2 were used (Peat30 (30cm Peat over 120cm Subsoil C) and FFM20 (20cm FFM over 130cm Subsoil C)) (Figure 2-1)
(2) Coversoil placement depth (soil cover treatments 1, 2, 3, and 4; i.e. (Peat 10 (10cm Peat over 140cm Subsoil C); Peat30 (30cm Peat over 120cm Subsoil C); FFM10 (10cm FFM over 140 cm Subsoil C); and FFM 20 (20cm FFM over 130cm Subsoil C)) (Figure 2-1)
(3) Different subsoil configurations with a 20cm FFM coversoil (soil cover treatments 2, 5, and 6 were used (Subsoil C (20cm FFM over 130cm Subsoil C); Subsoil BC (20cm FFM over 130cm Subsoil BC); and Subsoil Bm (20cm FFM over 30cm Subsoil Bm over 100cm Subsoil C)) (Figure 2-1).

2.2.3 Measurements

Prior to the first growing season, samples of all soil material types were collected from each soil treatment cell. Soil texture, pH, electrical conductivity (EC), sodium absorption ratio (SAR), organic matter content (OM), total organic carbon content (TOC), total organic nitrogen content (TON), and availability of nitrate (NO_3^-), ammonium (NH_4^+), phosphorus (P), potassium (K), and sulphate (SO_4^-) were tested on all samples (North Wind Land Resources Inc., 2013). Physical and chemical properties of the different materials are summarized in Table 2-1. Multiple monitoring systems were installed to record vadose zone water dynamics in all soil materials throughout 2013-2016. Two types of soil sensors were used to collect volumetric water content (VWC) and temperature data: 1) time domain reflectometry (TDR) sensors (Model 616, Campbell Scientific) were used to monitor *in situ* water content, and 2) thermal conductivity (TC) sensors (Model 229, Campbell Scientific) were used to monitor *in situ* temperatures. Sensors were installed 5cm/15cm (coversoil) and 35cm/45cm (subsoil) below the soil surface. Daily means from April through September were averaged to determine the average growing season soil temperature and VWC. Furthermore, the number of days with daily mean soil temperature above 5°C were calculated from 2013-2016 because root growth of most boreal tree species can be severely restricted below soil temperatures of 5°C (Chapin III, 1977; Karst & Landhäusser, 2014; Landhäusser et al., 2001).

A single square sub-plot (5m × 5m) was established in the center of each tree plot for the assessment of tree performance. Within the sub-plot, 16 seedlings were individually tagged and measured for heights (from ground to bud tip) and root collar diameter (RCD; at ground level) each August from 2012 to 2016. Additionally, two circular sub-plots with a radius of 2m were established in the NW and SE corners of each tree plot, and trees within each circle were assessed for the same parameters as the center sub-plot. Tree plot averages were calculated from the three subplots to asses total seedling height in 2016 and their relative growth, while the average of tagged trees from the center sub-plot were used exclusively for the 2012-2016 annual growth rates.

To explore early growth allocation of seedlings in response to coversoil material, three seedlings in each tree plot for all three species were excavated in treatments 1 and 2 in 2014. To avoid disturbing the seedling measurement plots through the excavation, we identified seedlings outside the measurement plots that were representative of each treatment using the average RCD of the trees in the measurement plots. Seedlings were carefully excavated to capture most of the root system and cold stored in the field, and then later frozen in the laboratory until the final processing. Roots, stems, and leaves were separated, and roots were carefully washed, dried at 70°C to constant weight, and dry mass (g) was measured. Subsamples of fresh leaves/needles were also used to measure projected leaf area, which was used to estimate total seedling projected leaf/needle area (cm^2) based on leaf mass. For this, aspen leaves were scanned with a LI-3100 Area Meter (LI-Cor Inc., Lincoln, USA), while pine and spruce needles were scanned using a STD4800 scanner and analyzed using the WinSEEDLE™ software (Regent Instruments Inc. Quebec, Canada).

2.2.4 Statistical Analysis

All analyses were conducted using R software, v 3.4.3, 64 bit (R Core Team, 2018a). Data for each question was averaged to the soil treatment cell level. Model residuals were tested for normality using the Shapiro-Wilk test from the R *stats* package (v 3.6.0; R Core Team, 2018b) and homogeneity of variance using Levene's test in the R *car* package (v 3.0-0; Fox et al., 2018); when data did not meet assumptions of normality or homogeneity, they were logarithmically transformed. Large operational scale studies like this generally have low replication, as a result we used $p \leq 0.1$ for all analyses to reduce the risk of Type II error.

Differences in overall soil characteristics (i.e. initial soil nutrients, chemical characteristics) between all soil types were analyzed using a permutational ANOVA from the *lmPerm* package in R (v 2.1.0; Wheeler et al., 2016). One-way ANOVAs using linear mixed effects models (LMM) in the *nlme* package (v 3.1-131; Pinheiro et al., 2018) were used to compare the 2011 soil textures of each material, seasonal VWC, average seasonal and annual soil temperature, and the number of days with average soil temperature above 5°C within each year (2013-2016), with soil treatment as the fixed effect and cell as the random effect.

To test the effects of coversoil material type, coversoil placement depth, and underlying subsoil treatments on annual tree growth from 2012 to 2016, a repeated measures ANOVA with LMMs was used, with soil treatment and year as the fixed effects and cell as the random effect. Comparisons of total tree height in 2016 were analyzed with fixed-effect linear models (LM) where soil treatment was set as the fixed effect. For the analysis of annual tree growth and total tree height in 2016 in response to coversoil depth, comparisons were individually made within each coversoil type. Total seedling biomass, leaf/stem/root mass and leaf area were exclusively compared between treatments 1 and 2 and analyzed with a one-way ANOVA using a full factorial design in the R *stats* package (v 3.6.0; R Core Team, 2018b). Interactions between the relative growth of all tree species and the soil treatments were analyzed with LMMs in a two-way ANOVA, where soil treatment and species were set as the fixed effects and cell as the random effect. All analyses, except for comparisons of relative growth among tree species, were run for each tree species separately.

When a significant main effect or an interaction were detected following any of the LMM analyses, LMMs were adjusted using the lsmeans function from the *lsmeans* package in R prior to running pair-wise comparisons (v 2.2-62; Lenth et al., 2018), and a Holm-Bonferonni adjusted $\alpha=0.1$ using the contrast function from the R *car* package was used to conduct Fisher's LSD pair-wise comparisons (v 3.0-0; Fox et al., 2018). Note, least-squared means and adjusted standard errors of annual tree growth are reported in Figures 2-3, 2-4, and 2-6, while original and unadjusted values are presented for all other data. For significant results found by a permutational ANOVA or fixed-effect LMs, the LSD.test function from the *agricolae* package was used to conduct pair-wise comparisons (v 1.2-8; de Mendiburu, 2017).

2.3 Results

2.3.1 Coversoil Material Type

Peat had a near-neutral pH and higher EC, SAR, OM, TOC, and TON than FFM ($p < 0.10$; Table 2-1). While significantly lower in plant available nitrate and sulfate, FFM was slightly acidic and contained more plant available phosphorus than Peat ($p < 0.10$; Table 2-1). FFM was coarse textured with 91.4% sand content, while mineral soil content in Peat was not measured (Table 2-1).

Peat (15cm below the soil surface) had lower annual and seasonal soil temperatures than FFM, except for the 2016 growing season ($p < 0.01$ each year (2013-2015); Table 2-2). From 2013 to 2016, Peat was on average 1.9°C colder; as a result, the Peat material had on average 8.4 fewer days each growing season where the daily average soil temperature was above 5°C ($p < 0.05$ each year; Table 2-2). Volumetric water content (VWC) 15cm below the soil surface was significantly higher in Peat for all years ($p < 0.001$ each year; Table 2-2). In the 2015 and 2016 growing seasons, water content at that depth never dropped below the wilting point for plants in the peat coversoil material (i.e. 25% VWC; Ojekanmi & Chang, 2014), whereas water content in the coarse-textured FFM repeatedly dropped below the wilting point of plants in sand (i.e. 5% VWC; Saxton & Rawls, 2006) for extended periods of time (Figure 2-2).

Aspen seedling growth steadily increased in 2013 and 2014 on FFM, while growth on Peat lagged ($p = 0.13$ in both years; Figure 2-3a). In 2015, which was a notably dry growing season (Figure 2-2; Section 2.1), growth of aspen in FFM decreased from the previous year, while it continued to increase in Peat; this pattern continued in the 2016 growing season (Figure 2-3a). Despite the decreased growth in FFM after 2015, aspen seedlings remained taller on the FFM compared to Peat by 2016 (total height: $p = 0.04$; Figure 2-3a). Taller aspen trees on the FFM also had higher stem and root mass in 2014 ($p < 0.1$ for both; Table 2-3). Pine seedling growth significantly increased on FFM in 2013 and 2014 compared to Peat ($p = 0.02$ for both years; Figure 2-3b). In 2015, pine improved growth over the previous years on both FFM and Peat materials, resulting in similar growth rates on both coversoil treatments that year (Figure 2-3b). In 2016, growth decreased at a similar rate for both FFM and Peat (Figure 2-3b). Due to the higher growth rates on the FFM in 2013-2014, pine seedlings were still overall taller in 2016 on FFM than on Peat (total height: $p = 0.03$; Figure 2-3b). The taller pine trees in the FFM also had higher total biomass, leaf, stem and root mass, and leaf area in 2014 ($p < 0.10$ for all; Table 2-3). Differences in growth of spruce as a result of coversoil did not become apparent until 2016, where spruce on Peat grew more than seedlings on the FFM ($p = 0.07$; Figure 2-3c). Although there were clear differences in growth by the fifth growing season, total seedling height of spruce in 2016 was similar between the two coversoil materials ($p = 0.58$; Figure 2-3c). Leaf area, total biomass, and root, stem, and leaf mass did not differ between the two coversoil materials in 2014 (Table 2-3).

When compared among species, relative growth of pine was the highest followed by aspen and spruce in both coversoil treatments (Figure A-2a). However, relative growth of pine and aspen differed between the two coversoils while it did not in spruce (coversoil × tree species interaction $p = 0.11$; Figure A-2a). Root collar diameter responses to placement depth treatments were similar to height growth in all species and are not presented.

2.3.2 Coversoil Placement Depth

Placement depth (10cm vs. 30cm) of Peat had a significant effect on soil temperatures measured at a soil depth of 35cm in all growing seasons, while placement depth did not influence soil temperature in the FFM placements (10cm vs. 20cm) (2013-2016; Table 2-2). Peat placed at 30cm was on average 2°C cooler each growing season compared to the 10cm placement of Peat ($p < 0.05$ all years; Table 2-2). The number of days where average daily soil temperatures were above 5°C in the 30cm of Peat had 15 and 10 fewer days than the 10cm Peat in 2014 and 2015, respectively ($p < 0.01$ in both years; Table 2-2). Despite being warmer than the 30cm of Peat, the 10cm of Peat remained cooler compared to the two FFM placements in 2013 and 2014 ($p < 0.10$ in both years; Table 2-2). Volumetric soil water content (VWC) at 5cm soil depth was significantly higher in 30cm of Peat ($0.37cm^3 \cdot cm^{-3}$) compared to 10cm of Peat ($0.21cm^3 \cdot cm^{-3}$), 10cm of FFM ($0.05cm^3 \cdot cm^{-3}$), and 20cm of FFM ($0.06cm^3 \cdot cm^{-3}$) each growing season ($p < 0.05$ for all). Similarly, VWC in 10cm of Peat was significantly higher than both FFM placement depths each growing season ($p < 0.05$ (2013-2014, 2016)); however, VWC was similar among the 10cm of Peat (0.16 $cm^3 \cdot cm^{-3}$) and FFM treatments (FFM10: 0.03 $cm^3 \cdot cm^{-3}$; FFM20: 0.04 $cm^3 \cdot cm^{-3}$) in the dry year of 2015 ($p = 0.18$).

Aspen seedling growth did not differ between the placement depth treatments for FFM in all years, while growth was lower on the 30cm of Peat compared to the 10cm of Peat in 2013 and 2014 ($p = 0.01$ in both years; Figure 2-4a). By 2016, however, the total height of aspen trees did not differ between the Peat placement treatments (Figure 2-4a). Pine seedling growth did not differ between the placement depths on the Peat and the FFM coversoils for any year (Figure 2-b). As mentioned in section 3.1, pine exhibited a sharp increase in growth regardless of coversoil and placement depth treatment in 2015 (Figure 2-4b). In 2016, the total height of pine seedlings did not differ between the placement treatments in FFM and Peat (Figure 2-4b). Spruce seedling growth was slightly higher on the 30cm of Peat compared to 10cm of Peat in 2015, and this difference became significant in 2016 ($p = 0.06$; Figure 2-4c). Total height of spruce trees measured in 2016 did not differ between the placement depths for FFM or Peat (Figure 2-4c).

When comparing growth among species, pine had the highest relative growth compared to the other two species in the 10cm and 30cm placement depths of Peat (Figure A-2b). However, while aspen and pine positively responded to the thinner placement of Peat, spruce did not, resulting in a significant peat thickness by tree species interaction ($p = 0.09$; Figure A-2b). No interactions were found between placement depth and tree species in the FFM treatments. Root collar diameter responses to placement depth treatments were similar to height growth in all species and are not presented.

2.3.3 Subsoil Material

All three subsoils were classified as sands; however, Subsoil BC had a lower silt content (1.3%) compared to Subsoils Bm and C (2.4% and 3.7%, respectively; $p < 0.05$ for Bm vs. C only; Table 2-1). There were significant differences in pH between the subsoil materials, where pH was the highest in the BC (7.13) and lowest in the Bm (6.04) subsoil ($p < 0.1$; Table 2-1). The Subsoil Bm had higher plant available phosphorus compared to the other two subsoil materials ($p < 0.1$; Table 2-1).

Average seasonal VWC measured in the subsoil 45cm below the soil surface was similar across all subsoil materials ($p = 0.150$; Subsoil Bm: 0.097cm^3·cm^{-3}; Subsoil BC: 0.108cm^3·cm^{-3}; Subsoil C: 0.097cm^3·cm^{-3}). A subsoil treatment by year interaction was found in VWC 45cm below the soil surface ($p = 0.04$) resulting from a drop in VWC in the BC material compared to the other subsoils in 2015 (data not shown). Volumetric soil water content measured in the rooting zone (15cm depth) was similar among the three subsoils in the 2013 and 2014 growing seasons (2013: $p = 0.83$; 2014: $p = 0.39$; Figure 2-5). However, in 2015 when VWC decreased in all subsoil treatments, VWC in the Subsoil BC fell below the wilting point for plants in sand (i.e. 5% VWC; Saxton & Rawls, 2006), whereas Subsoils Bm and C remained above the threshold during these periods (subsoil × year interaction p = 0.02; Figure 2-5). By 2016, VWC remained below the wilting point in the Subsoil BC, while VWC increased in the Subsoil Bm and C treatments (Figure 2-5).

Aspen seedling growth increased starting in 2014 on the Subsoil Bm and C treatments, while growth remained unchanged on the Subsoil BC treatment (Figure 2-6a). In the dry year of 2015, growth started to decrease in the Subsoil BC treatment compared to Subsoil Bm and C ($p < 0.2$ for both comparisons; Figure 2-6a), and in the following growing season, aspen growth on the Subsoil BC treatment became significantly lower compared to Subsoil Bm ($p = 0.01$) and C ($p = 0.07$) (Figure 2-6a). By 2016, aspen seedlings were tallest on the Subsoil Bm treatment and shortest on the treatments with Subsoil BC ($p = 0.002$) and C ($p = 0.01$; Figure 2-6a). Despite the reduced height growth of aspen on the Subsoil BC, RCD growth remained equal and consistent to seedlings grown in the other subsoils in 2014 (Bm: 19.4mm, BC: 16.6mm, and C: 16.3mm) and 2016 (Bm: 26.6mm, BC: 22.7mm, and C: 22.3mm). Pine seedling growth rates started to differentiate in 2015 when seedlings grew slower on the Subsoil BC compared to the Subsoil Bm ($p = 0.002$) and Subsoil C ($p = 0.002$) (Figure 2-6b); however, pine growth decreased similarly on all subsoil treatments during the 2016 growing season, resulting in no differences in growth that year (Figure 2-6b). In 2016, total height of pine was greatest on treatments with Subsoils Bm and C compared to Subsoil BC (p = 0.03 and p = 0.04; respectively; Figure 2-6b). Root collar diameter of pine followed the same trends as height growth and this data is not shown. Spruce seedling growth only differed in 2014, where seedlings grew less on Subsoil C compared to the Subsoil Bm (p = 0.16) and BC (p = 0.04) (Figure 2-6c). By 2016, total height of spruce was similar among subsoil treatments (p = 0.65; Figure 2-6c). Root collar diameter of spruce followed the same trends as height growth and this data is not shown.

Relative growth differed among the three species, where pine had the greatest relative growth, followed by aspen, and spruce across all subsoil treatments (Figure A-2c). Pine relative growth positively responded to the Subsoil Bm and C treatments, aspen responded more to the Subsoil Bm, and spruce did not respond to any subsoil treatment (subsoil × tree species interaction: p = 0.01; Figure A-2c).

2.4 Discussion

The type and amount of coversoil material placed at the soil surface had the greatest overall impact on early seedling growth (first five growing seasons) in our study. Aspen and pine responses were more pronounced on the two coversoil types and placement depths compared to spruce. Overall, both species grew significantly taller on the salvaged upland FFM compared to the lowland Peat coversoil (Figure 2-2, Figure 2-3, Figure A-2a, Figure A-2b). We identified potentially three factors and their interactions that could have affected resource availability and impacted seedling and species responses to the coversoil treatments. Differences could have been driven by the availability of less mobile nutrients such as phosphorus and by differences in the physical conditions of the coversoils (i.e. soil temperature and water holding capacity), which in turn affect resource availability (i.e. nutrients and water) (Table 2-1, Table 2-2). Pioneer tree species, such as aspen and pine, rely heavily on the availability of essential nutrients, water supply, and warm soil temperatures to accommodate their early fast growth rates during establishment (Chapin III et al., 1986; Chapin III et al., 1983). The greater sensitivity of these species to soil conditions compared to white spruce partly explains their reduced growth rates observed on the Peat coversoil, with significantly lower levels of phosphorus and lower soil temperatures compared to the FFM (Table 2-1, Table 2-2). It also explains the decrease in aspen growth on the FFM when water availability became limiting during the dry growing conditions of 2015 compared to the wetter Peat coversoil (Figure 2-2). These strong responses are in contrast to white spruce, which responded comparatively weakly to the changing conditions. This was somewhat expected, as the relatively slower growing spruce is more tolerant to nutrient limitations and cooler root zone temperatures (Chapin III, 1977; Landhäusser et al. 2001, 2003; Zhang et al., 2013; Karst & Landhäusser 2014).

Despite the phosphorus limitations, Peat had higher levels of plant available nitrogen, potassium, and sulfur, and SOM (Table 2-1). While an abundance of SOM is beneficial for long-term nutrient cycling, the considerably higher SOM content in Peat compared to FFM had the greatest effect on root zone conditions. Peat can exhibit varying physical and chemical characteristics based on the source material and its degree of decomposition (Hayward & Clymo, 1982; Rezanezhad et al., 2010); however, a common property associated with peat is its strong insulative abilities. In permafrost regions, the surface layers of peat will dry during the summer months, creating conditions of low thermal conductivity that increase temperature insulation with increasing soil depth; furthermore, peat can absorb large volumes of water that freeze during winter, increasing the thermal conductivity and subsequent penetration of sub-zero temperatures to greater depths (Nelson et al., 1985). In reclaimed mixtures of peat-mineral materials, Zhao & Si (2019) reported a decrease in thermal conductivity with an increase in the peat:mineral ratio, which corresponded with a subsequent decrease in soil temperature.

In our study, the insulative properties and high soil water content of Peat consistently delayed warming of the root zone each spring (Table 2-2), slowing the metabolic activity and overall uptake of water and nutrients in the root zone, and inhibiting important physiological processes such as root, leaf, and shoot growth (Table 2-3) (Landhäusser et al., 2001; 2003; Wan et al., 1999; Wolken et al., 2011). These low soil temperatures can also affect root-water dynamics in aspen seedlings by reducing water uptake, which directly impacts the uptake of nutrients and slows important functions such as stomatal conductance and net photosynthesis (Wan et al., 1999). In addition, cooler soil conditions resulted in delays at the start of each growing season, which likely led to the slower growth rates and shorter seedlings, particularly in aspen and pine, by the fifth growing season (Figure 2-3). Root growth of most boreal tree species is considered to be limited below soil temperatures of 5°C, although some species, such as white and black spruce, are more tolerant of low soil temperatures (Chapin III, 1977). Landhäusser et al. (2001) found minimal shoot and root growth in aspen when soil temperatures were below 5°C compared to seedlings grown at 25°C, while spruce showed no change in response to the same soil temperatures. Pine seedlings have shown sensitivity to low soil temperatures, resulting in reduced below- and aboveground growth rates (Karst & Landhäusser, 2014; Peng & Dang, 2003).

This relationship between soil temperature and seedling growth response was also apparent when comparing tree growth of aspen and pine between the shallow and deep Peat coversoil treatments, where seedlings negatively responded to the thicker 30cm placement of Peat (Figure 2-4; Figure A-2b). The shallow Peat and FFM depth treatments had similar soil temperature and moisture conditions at 35 cm below the surface, where soil temperatures were warmer than the thick Peat treatment (Table 2-2): these results demonstrate the soil temperature limitations introduced when placing SOM in thick layers at the soil surface. In a study of seedling survival following forest fire in the Canadian boreal, Greene et al. (2007) found a negative correlation between trembling aspen, jack pine, and black spruce with SOM thickness. Others suggested a layer greater than 20-30cm of SOM will limit trembling aspen distribution, while black spruce can benefit from the insulative properties of thick SOM layers due to its shallow root system (Gewehr et al., 2014; Lafleur et al., 2015). The white spruce seedlings in our study alluded to the relationship between black spruce and SOM layers, where seedlings had a slight positive response to the thicker placement of Peat, providing additional support to the ability of this species to maintain growth in cooler soil temperatures (Landhäusser et al., 2003; Wolken et al., 2011).

While the high SOM and associated insulative properties of Peat created temperature limitations, there is a potential trade-off with the ability of peat to store and supply water to the vegetation. This trade-off became evident during the very dry conditions of 2015-2016, where trees grew noticeably less in the thin Peat (10cm) and the FFM coversoil treatments compared to the thicker Peat (30cm) treatment (Figure 2-4). When combined with the soil water content data, water availability from the upper surface layers where most roots are located suggest that the thin Peat and the FFM coversoil treatments did not hold enough water to buffer against the dry growing conditions of 2015 (Section 2.3.2). Water availability in the FFM was low as VWC reached the permanent wilting point (PWP) of sandy soil textures for extended periods during the 2015 and 2016 growing period; alternatively, VWC in Peat remained above the PWP for this material type and provided seedlings with enough water to maintain growth. Limited water availability negatively affects photosynthetic processes and reduces the uptake of nutrients that are essential for physiological functions (Fageria, 2013; Kreuzwieser & Gessler, 2010); thus, it is important to consider the cover soil materials and their water storage capabilities during dry growing seasons. These findings indicate the important role that Peat materials can have in soil water and plant dynamics on upland forest reclamation, especially if there is a prolong period of drought conditions or if dry growing conditions become more frequent with a changing global climate (Kreuzwieser & Gessler, 2010; Krishnan et al., 2006).

Interestingly, pine seedlings grew more during the dry season of 2015 compared to the other years measured (Figure 2-3b, Figure 2-4b). This greater growth response in pine may have partially been influenced by the conditions of the previous growing season, where the area received above average precipitation during the time when the new buds for 2015 were formed (Burns & Honkala, 1991). Therefore, an early spring in 2015 coupled with the effects of a wet 2014 season may have been the cause for greater pine growth in 2015 (Table 2-2); however, the effects of the dry 2015 growing season were noticeable in the growing season following the dry year when pine growth decreased significantly (Figure 2-3b, Figure 2-4b).

While the type of coversoil had a substantial effect on the growth response of our seedlings, the type of subsoil material placed below the coversoil also had a measurable effect on early seedling establishment and growth. Since the root growth of seedlings on the Peat coversoil was very limited in the first five growing seasons, potential responses to the different subsoil treatments were likely constrained and obscured by the strong coversoil effect. Thus, we used the FFM capped subsoil treatments to explore these responses to different subsoils as the seedlings had much larger tree root systems that had accessed the underlying subsoil materials later in the study period. Some of the differences we detected among the different subsoil types appear to be driven by the availability of mineral nutrients. Layering the soil profile with a selectively salvaged Bm subsoil was designed to mimic a weathered subsoil layer found in Brunisolic soils. The other two subsoil treatments (BC and C) represent a more operational and economical approach where the B and C horizons are salvaged together and placed on site somewhat blended and homogenized. While this is more cost-effective, an increased proportion of the lower C horizon in the subsoil layer will subsequently dilute the nutrients that can be found concentrated in the weathered B horizon (Ojekanmi & Chang, 2014), which is noticeable when comparing the higher concentrations of phosphorus in the Subsoil Bm layer to the homogenous BC and C subsoils (Table 2-1). Despite the additional supply of phosphorus in this subsoil, aspen was the only species that responded positively to the Subsoil Bm treatment (Figure 2-6; Figure A-2c). Aspen is known for investing more resources into root systems during the early years of establishment, growing expansive and deep roots for rapid access to available nutrients in the deeper soil layers compared to pine and spruce (Strong & La Roi, 1983a; Strong & Roi, 1985). However, the greater root growth is also associated with a greater demand for essential nutrients and with greater phosphorus availability in the weathered layer of the Bm treatment, aspen would have had access to this nutrient, provided other essential nutrients were not becoming limited as their roots expanded deeper into the soil profile (Chapin III et al., 1986; Chapin III et al., 1983; Pinno et al., 2012a).

Water availability was another potential driver that could have affected the growth response of the seedlings to the different subsoils. Although the three subsoils were classified as sands (Table 2-1), average daily water content during the very dry 2015-growing season was significantly higher at 15cm depth in soils reconstructed with Subsoil C compared to Subsoil Bm or BC (Figure 2-5). Although the subsoil materials had similar textures and bulk densities, there were slight but significant differences in silt content that corresponded with the average water content each growing season. The Subsoil C treatment had the highest silt and water content and Subsoil BC had the lowest. Studies on coarse-textured boreal soils reported that even small differences in silt content (1 - 3%) between the subsoil horizons can make a large difference in the water holding ability of sandy soils (Gale & Grigal, 1987; Huang et al., 2013; Jung et al., 2014; Zettl et al., 2011). The slightly higher silt contents in the treatments with Subsoil Bm or Subsoil C may have held more water in the root zone by slowing drainage past the FFM and subsoil interface, which could explain the higher water content measured 15cm below the soil surface compared to 45cm (Section 2.3.3).

Large controlled reclamation field studies like the ASCS are rare and provide a unique opportunity to test a range of ecological questions that are difficult to conduct in natural environments. In this study, mixing a coarse mineral soil material (particularly the surface Bm material) with the peat could have potentially provided an opportunity to develop a surface soil material that balances nutrient availability with higher water holding capacity for trees during dry years, as well as warmer soils and faster spring warming compared to a peat-only coversoil. Similarly, the coarse FFM could have benefitted by amending it with Peat to improve the water holding capacity of this otherwise suitable coversoil during dry growing conditions and providing more suitable seedbeds for the upland propagules that were retained in the salvaged FFM (Jones & Landhäusser. 2018). While the root systems of most tree species were just starting to explore the deeper soil layers in this study, there were indications that the type of subsoil material will impact the growth of trees and possibly their resilience to stresses such as drought in the long-term. The dry conditions observed in the latter years of this study demonstrate how textural heterogeneity may be important for improving water availability in coarse-textured subsoils. Furthermore, the placement of selectively salvaged and weathered subsoils may provide additional nutrients as tree roots continue to grow deeper into the reconstructed soil profile. The knowledge gained from this study will be useful in the development of operational criteria for reconstructing soil covers used in boreal forest reclamation, while informing the impacts of soil covers on afforestation success and furthering the development of functional and sustainable forest ecosystems.

2.5 Tables

Table 2-1: Summary of physical and chemical properties of the soil material types in 2012. Values represent adjusted means (±SD) from the a) least-square means results for particle size data, and b) Fisher's LSD test results for all other data listed in the table. Letters indicate a significant difference among treatments (α≤0.1).

		Peat	FFM	Subsoil Bm	Subsoil BC	Subsoil C
Sample Size		36	36	24	24	24
Cap Depth (cm)		10/30	10/20	30	130	100-130
Salvage (cm)		0-300	0-15	15-50	50-100	15-250
Particle Size Distribution (%)†	Sand	NM	91.4^{B} (2.8)	93.3^{A} (1.6)	93.8^{A} (2.6)	92.2^{AB} (5.8)
	Silt	NM	4.1^{A} (2.2)	2.4^{BC} (1.3)	1.3^{C} (1.2)	3.7^{AB} (4.1)
	Clay	NM	4.5 (0.9)	4.3 (0.7)	4.9 (1.5)	4.3 (1.8)
pH		7.47^{A} (0.19)	5.68^{E} (0.39)	6.04^{D} (0.47)	7.13^{B} (0.36)	6.76^{C} (0.76)
EC ($dS{\cdot}m^{-1}$)		1.25^{A} (0.32)	0.21^{B} (0.07)	0.17^{B} (0.06)	0.20^{B} (0.06)	0.19^{B} (0.16)
SAR		0.76^{A} (0.53)	0.20^{C} (0.04)	0.21^{C} (0.04)	0.30^{B} (0.27)	0.32^{B} (0.18)
OM (%)		31.2^{A} (11.7)	2.7^{B} (0.9)	NM	NM	NM
TOC (%)		15.6^{A} (5.8)	1.3^{B} (0.5)	NM	NM	NM
TON (%)		0.65^{A} (0.27)	0.04^{B} (0.01)	NM	NM	NM
Available Nutrients ($mg\ kg^{-1}$)	NO_3^-	9.0^{A} (10.3)	2.0^{B} (0.0)	2.3^{B} (0.9)	2.0^{B} (0.0)	2.0^{B} (0.0)
	NH_4^+	1.0^{B} (0.4)	1.9^{A} (2.4)	0.3^{C} (0.1)	0.3^{C} (0.0)	0.4^{C} (0.1)
	P	5.0^{D} (0.0)	25.6^{A} (4.8)	27.6^{A} (10.0)	11.5^{B} (3.8)	8.7^{C} (2.9)
	K	39.4^{A} (13.7)	41.1^{A} (12.7)	26.5^{B} (5.1)	24.8^{B} (2.5)	26.1^{B} (6.0)
	SO_4^-	412.9^{A} (133.7)	5.3^{B} (2.3)	2.7^{B} (2.0)	2.6^{B} (1.7)	2.8^{B} (2.2)

Note: 'EC' refers to electrical conductivity, 'SAR' refers to sodium adsorption ratio, 'OM' refers to organic matter, 'TOC' refers to total organic carbon, 'TON' refers to total organic nitrogen, and 'NM' refers to not measured. † represents data that was logarithmically transformed prior to analysis.

Table 2-2: Mean (±SD) annual and growing season soil temperature, number of days with an average daily soil temperature above 5°C, and volumetric soil water content (VWC) at both 15cm and 35cm below the soil surface in FFM and Peat materials from 2013 to 2016 (n=3). Letters indicate statistically significant differences between means within each response variable and each year (α=0.1).

		2013				2014				2015				2016			
		Peat		FFM		Peat		FFM		Peat		FFM		Peat		FFM	
	Placement Depth	†10 cm	30 cm	10 cm	20 cm	10 cm	30 cm	10 cm	20 cm	†10 cm	†30 cm	10 cm	20 cm	10 cm	30 cm	†10 cm	20 cm
Sensor Depth 15 cm	Annual soil temperature (°C)	3.8^{B}	4.0^{B}	6.0^{A}	6.0^{A}	3.5^{G}	2.7^{G}	5.4^{F}	5.1^{F}	6.1^{L}	4.3^{M}	7.6^{L}	6.1^{L}	5.7^{Y}	5.1^{Y}	10.2^{X}	6.3^{Y}
		(0.7)	(0.4)	(0.1)	(0.2)	(0.6)	(0.2)	(0.1)	(0.1)	(0.9)	(0.3)	(0.1)	(0.2)	(0.3)	(0.2)	(0.9)	(0.4)
	Seasonal soil temperature (°C)	11.3^{B}	11.1^{B}	13.3^{A}	13.7^{A}	10.5^{G}	10.0^{G}	12.1^{F}	12.3^{F}	12.2^{LM}	11.2^{M}	12.8^{L}	12.9^{L}	12.8^{X}	12.4^{X}	12.7^{X}	13.5^{X}
		(0.6)	(0.3)	(0.5)	(0.2)	(0.6)	(0.3)	(0.5)	(0.3)	(0.8)	(0.2)	(0.5)	(0.6)	(0.5)	(0.0)	(0.5)	(0.7)
	# of days with average temp > 5°C	140.7^{B}	138.0^{B}	149.3^{A}	149.3^{A}	140.0^{GH}	138.3^{H}	146.0^{F}	144.7^{FG}	149.0^{MN}	144.3^{N}	159.0^{L}	156.0^{LM}	159.0^{X}	156.0^{X}	139.3^{Y}	160.3^{X}
		(1.5)	(0.6)	(1.2)	(0.7)	(1.7)	(0.9)	(3.1)	(0.3)	(5.0)	(0.3)	(1.0)	(2.1)	(1.7)	(0.0)	(11.2)	(2.8)
	VWC (cm^3 cm^{-3})	0.09^{B}	0.44^{A}	0.09^{B}	0.10^{B}	0.09^{G}	0.45^{F}	0.08^{G}	0.10^{G}	0.08^{M}	0.44^{L}	0.07^{M}	0.08^{M}	0.08^{Y}	0.43^{X}	0.08^{Y}	0.09^{Y}
		(0.01)	(0.04)	(0.01)	(0.01)	(0.01)	(0.05)	(0.01)	(0.01)	(0.01)	(0.06)	(0.01)	(0.01)	(0.01)	(0.05)	(0.00)	(0.01)
Sensor Depth 35 cm	Annual soil temperature (°C)	4.2^{B}	4.3^{B}	6.1^{A}	6.1^{A}	3.5^{G}	2.4^{H}	5.4^{F}	5.2^{F}	6.1^{L}	4.0^{M}	6.5^{L}	6.0^{L}	5.8^{Y}	5.0^{Z}	6.8^{X}	6.4^{XY}
		0.5	0.5	0.0	0.2	0.5	0.3	0.1	0.2	0.9	0.3	0.3	0.1	0.2	0.1	0.5	0.2
	Seasonal soil temperature (°C)	10.7^{B}	9.4^{C}	12.0^{A}	12.2^{A}	9.6^{G}	7.4^{H}	10.8^{F}	10.8^{F}	11.4^{L}	8.7^{M}	11.5^{L}	11.5^{L}	12.2^{X}	10.2^{Y}	12.0^{X}	12.4^{X}
		(0.5)	(0.2)	(0.4)	(0.2)	(0.5)	(0.4)	(0.4)	(0.2)	(0.6)	(0.3)	(0.3)	(0.4)	(0.5)	(0.3)	(0.5)	(0.5)
	# of days with average temp > 5°C	126.0^{B}	135.0^{AB}	144.3^{A}	141.3^{AB}	136.0^{F}	121.3^{G}	140.3^{F}	138.0^{F}	143.3^{M}	133^{N}	154^{L}	147^{M}	155.0^{X}	146.7^{X}	143.3^{X}	156^{X}
		(13.1)	(2.3)	(1.5)	(0.7)	(1.2)	(5.8)	(0.9)	(0.6)	(0.9)	(3.2)	(1.5)	(1.5)	(0.6)	(3.8)	(15.8)	(0.6)
	VWC (cm^3 cm^{-3})	0.08^{A}	0.08^{A}	0.08^{A}	0.10^{A}	0.08^{G}	0.08^{G}	0.08^{G}	0.10^{F}	0.07^{M}	0.08^{LM}	0.08^{LM}	0.09^{L}	0.08^{X}	0.08^{X}	0.09^{X}	0.10^{X}
		(0.00)	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.01)

† represents soil treatments with missing data during the growing season.

Table 2-3: Mean (±SD) of leaf area (cm^2), total biomass, leaf, stem and root mass (g) in 2014 of aspen, pine and spruce on FFM and peat materials (n=3). Different letters indicate statistically significant coversoil effects within each species (α≤0.1).

		(cm^2)	(g)			
Species	Topsoil material	Leaf area	Total biomass	Leaf mass	Stem mass	Root mass
Aspen	FFM	5825^{a} (503)	338^{a} (13)	54.5^{a} (2.3)	122.6^{a} (10.2)	161.3^{a} (7)
	Peat	3099^{a} (2506)	180^{a} (130)	32.9^{a} (24.4)	61.4^{b} (48.2)	85.5^{b} (59.5)
Pine	FFM	6125^{s} (1091)	246^{s} (37)	123.4^{s} (21.5)	91.7^{s} (11)	31.3^{s} (6.9)
	Peat	2592^{t} (1636)	108^{t} (68)	55.3^{t} (34.4)	38^{t} (26.2)	15^{t} (8.1)
Spruce	FFM	2852^{x} (692)	121^{x} (30)	56.1^{x} (12.1)	44.8^{x} (11.8)	20.4^{x} (6.6)
	Peat	1924^{x} (1237)	100^{x} (58)	36.3^{x} (21.9)	43.2^{x} (25.2)	20.2^{x} (11)

2.6 Figures

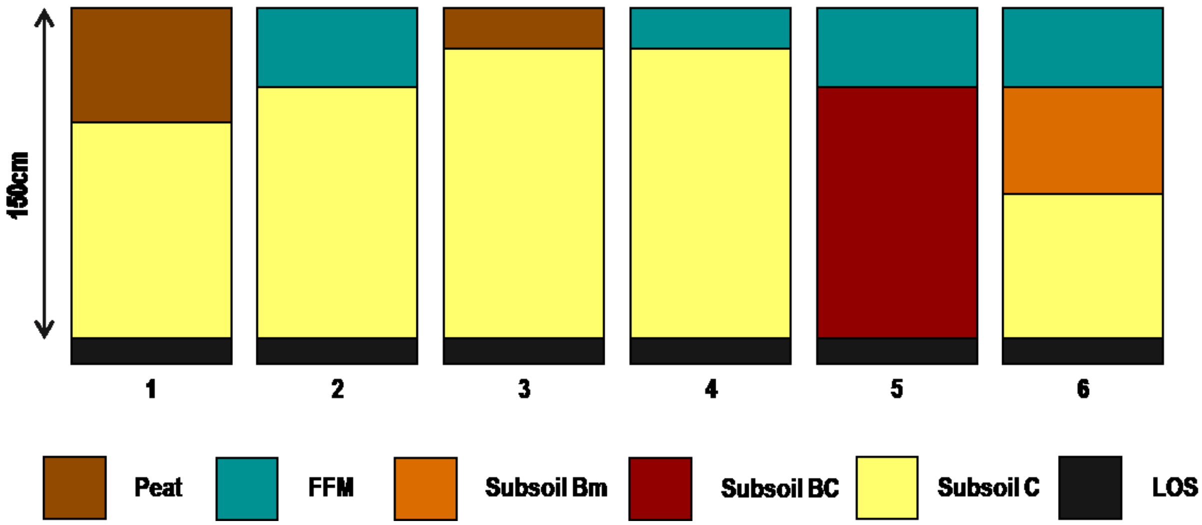

Figure 2-1: Six of the thirteen soil layering treatments at the Aurora Soil Capping Study (ASCS) are shown. Treatment 1 is 30cm of Peat over 120cm of Subsoil C; treatment 2 is 20cm of FFM over 130cm of Subsoil C; treatment 3 is 10cm of Peat over 140cm of Subsoil C; treatment 4 is 10cm of forest floor material (FFM) over 140cm of Subsoil C; treatment 5 is 20cm of FFM over 100cm of Subsoil C, and; treatment 6 is 20cm of FFM over 30cm of Subsoil Bm over 100cm of Subsoil C. All treatments were placed over lean oil sands (LOS) overburden material. Physical and chemical characteristics of these materials are presented in Table 2-1.

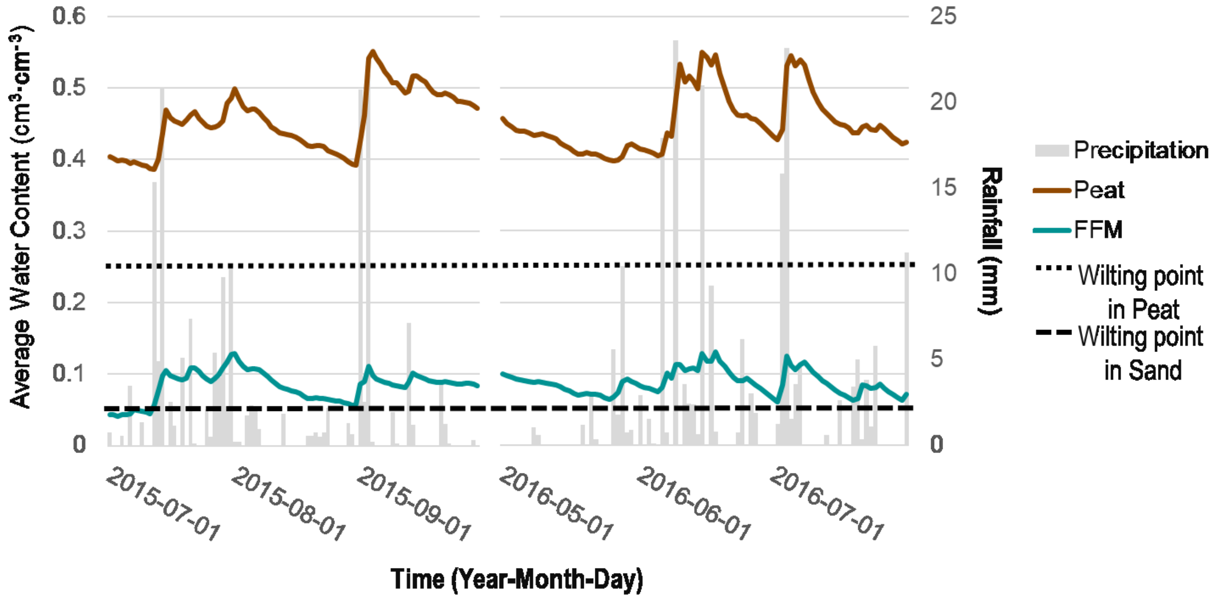

Figure 2-2: Average daily volumetric water content for parts of the 2015 and 2016 growing seasons. Bars represent daily precipitation. Dashed lines represent an approximation of the wilting point for plants growing in peat (0.25 $cm^3 \cdot cm^{-3}$; 25% VWC) and sand (0.05 $cm^3 \cdot cm^{-3}$; 5% VWC) (Ojekanmi & Chang, 2014; Saxton & Rawls, 2006).

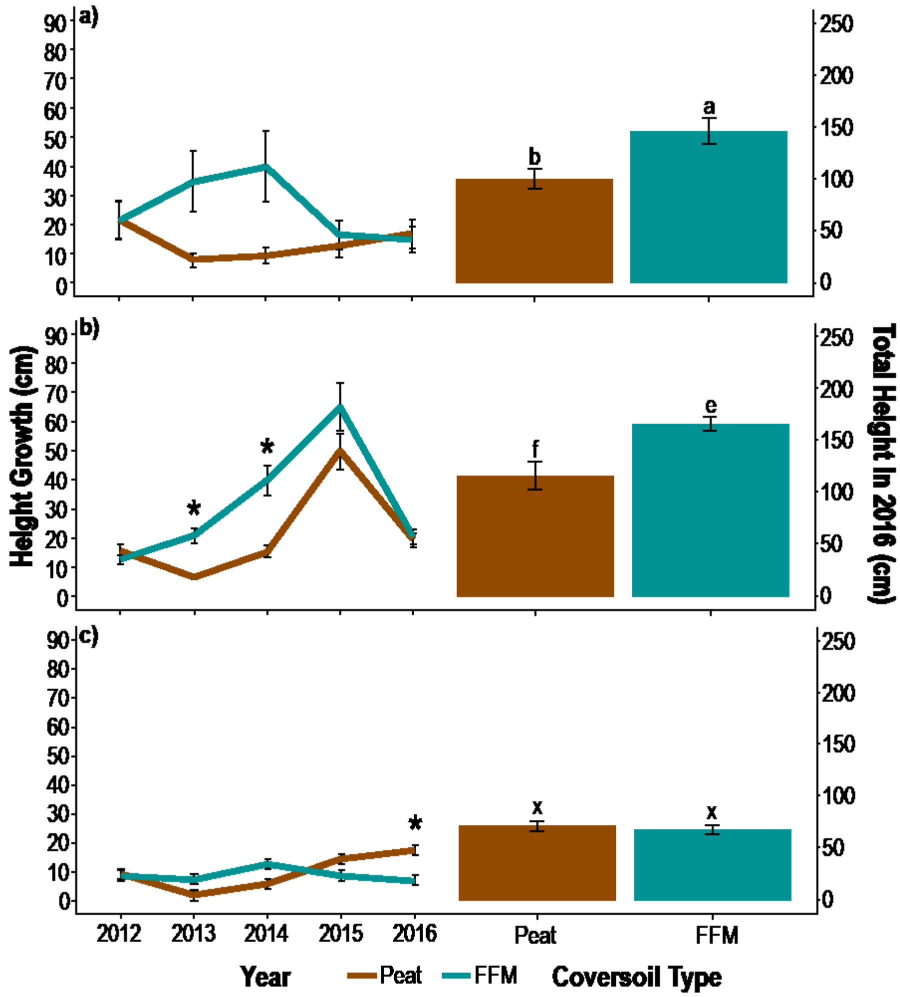

Figure 2-3: Mean (±SE) tree growth during the first five growing seasons (left panel) and average total tree height measured in 2016 (right panel) for trembling aspen (a), jack pine (b), and white spruce (c) growing in two coversoil material types. Asterisks (*) indicate significant differences between treatment growth means within a year, and different letters indicate significant differences between total heights (α≤0.1, n=3).

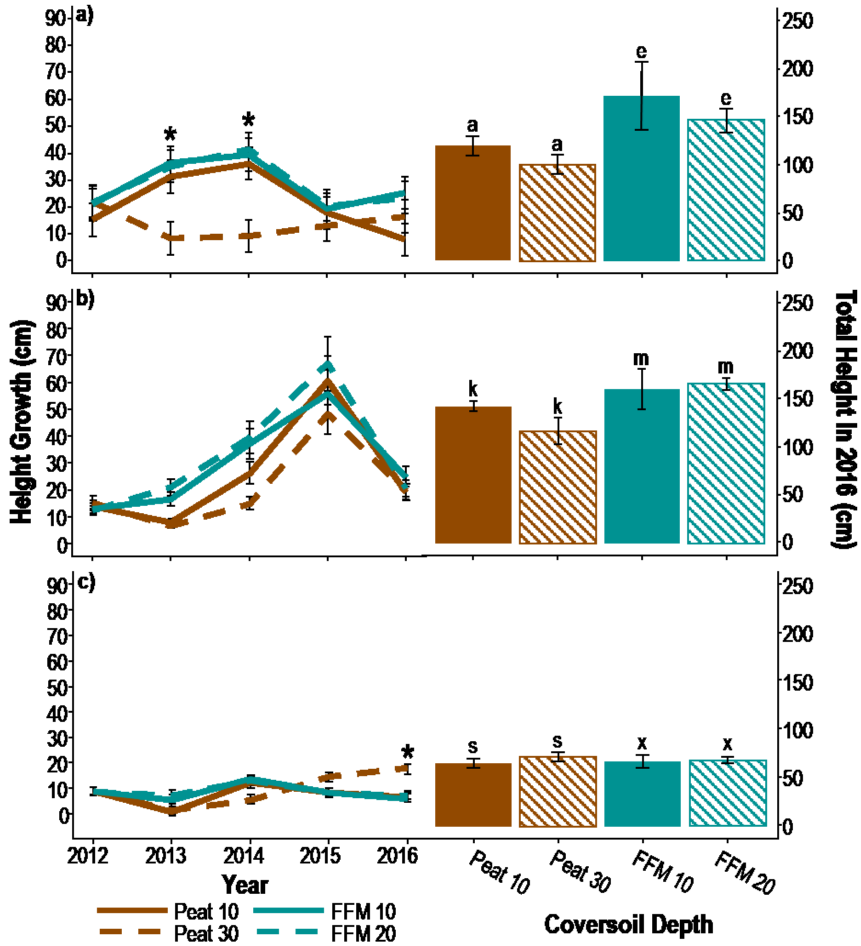

Figure 2-4: Mean (±SE) tree growth during the first five growing seasons (left panel) and average total tree height measured in 2016 (right panel) for trembling aspen (a), jack pine (b), and white spruce (c) in four coversoil placement depths. Asterisks (*) indicate significant differences between growth means of Peat or FFM depth treatments within a year, and different letters indicate significant differences between total heights within each coversoil type (α≤0.1, n=3).

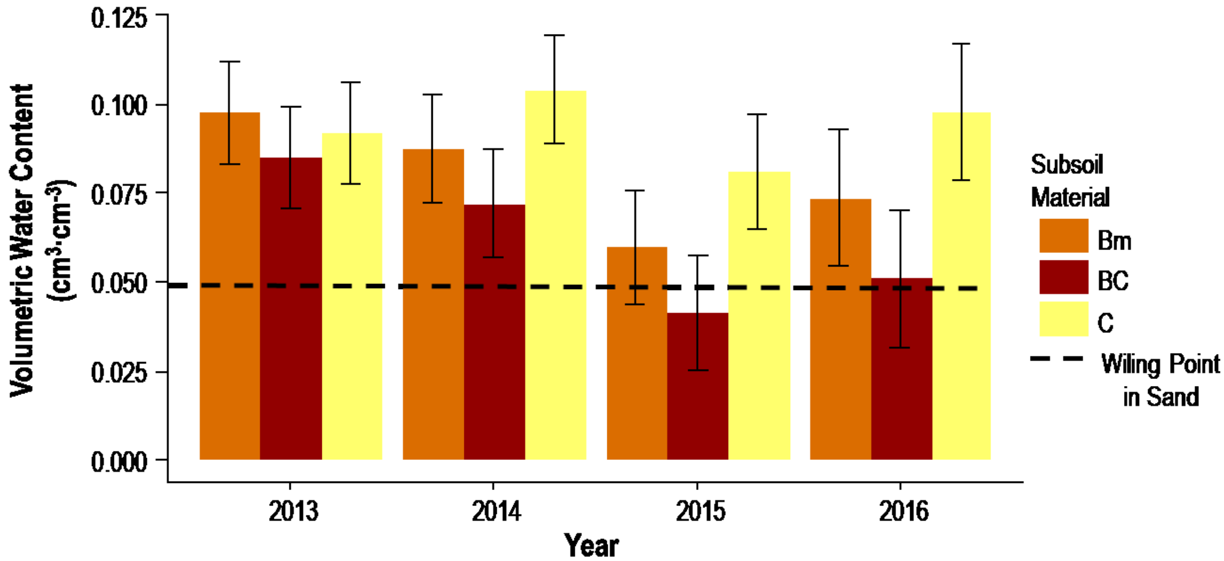

Figure 2-5: Mean (±SE) growing season volumetric water content 15cm below the soil surface in FFM treatments underlain by different subsoil materials in 2013, 2014, 2015, and 2016 (n=3).

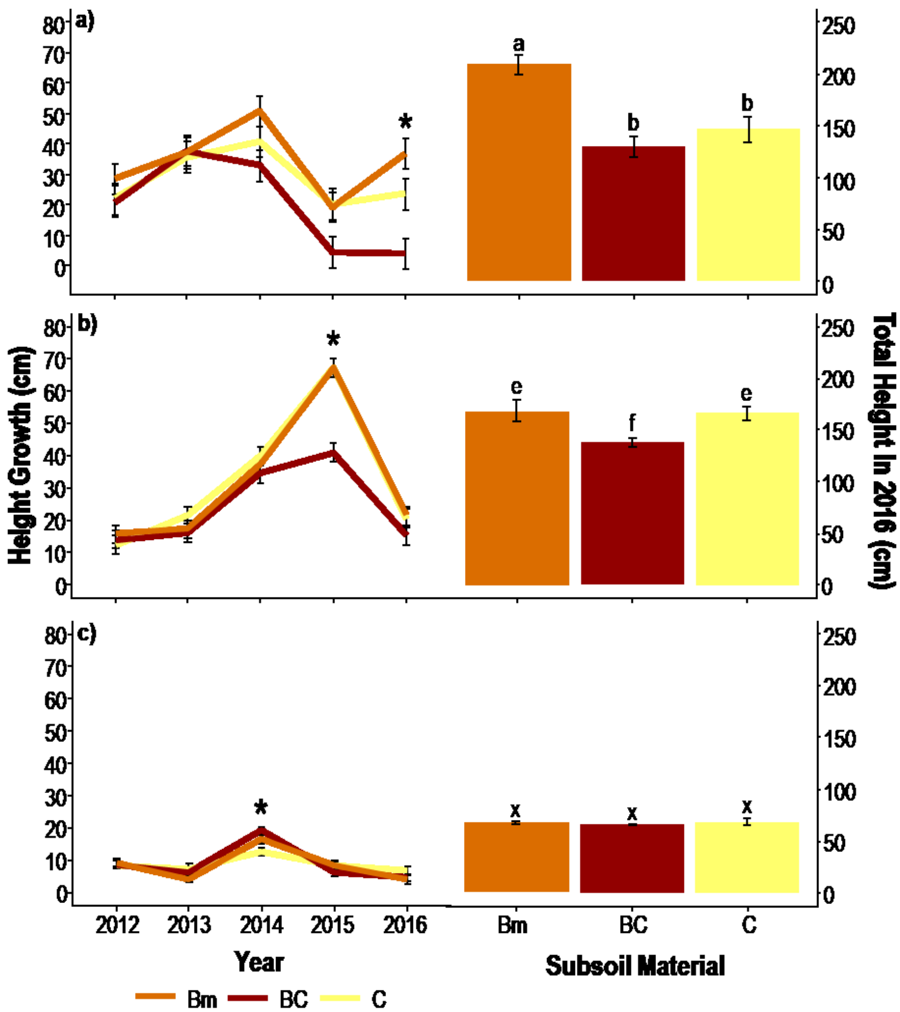

Figure 2-6: Mean (±SE) tree growth during the first five growing seasons (left panel) and average total tree height measured in 2016 (right panel) for trembling aspen (a), jack pine (b), and white spruce (c) growing in three subsoil material types. Asterisks (*) indicate significant differences between treatment growth means within a year, and different letters indicate significant differences between total heights (α≤0.1, n=3).

Chapter 3: Species specific responses to targeted fertilizer application on reconstructed soils in a reclaimed upland area

3.1 Introduction

The establishment of native vegetation on reclaimed lands is a critical step in the successful restoration of functional forests in post-mined areas (Burton & Macdonald, 2011; Jacobs et al., 2015; Pickell et al., 2013). Creating a rooting medium that can support a diverse and dynamic forest cover can be challenging if there are limitations associated with the soil materials used in forest reclamation and the underlying substrate or landform that is being reclaimed (Macdonald et al., 2015b; Zipper et al., 2013). Substrates that have chemical and/or physical limitations require the placement of a suitable soil cover using salvaged organic coversoils placed over salvaged mineral subsoils (Cumulative Environmental Management Association, 2009; Oil Sands Vegetation Reclamation Committee, 1998). These soil reclamation materials must meet the demands of planted mixed-species seedlings that exhibit a variety of adaptations and resource requirements (Beckingham & Archibald, 1996; Burns & Honkala, 1990). The soil organic matter within the coversoil layer is important for initiating short-term nutrient cycling and providing water storage for early vegetation establishment and growth (Berg & Laskowski, 2005; Mcgill & Cole, 1981; Zhuang et al., 2008), while the underlying subsoil materials provide long-term nutrient availability through weathering, water storage, and structural support for deep-rooted and long-lived plants (Jung et al., 2014; Strong & La Roi, 1983a).

Soil fertility plays a critical role in supporting the early establishment of planted seedlings that require an ample supply of essential nutrients to sustain their rapid growth rates (Cole, 1995). There are six nutrients that are highly correlated in their importance for plant function and growth, and these include nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg). Both N and S are important components of proteins and amino acids (Garten Jr, 1976), while N and P are closely associated in photosynthetic processes, cytoplasmic and nuclear material structure, and protein synthesis (Reich & Schoettle, 1988; Schachtman et al., 1998). Potassium is a highly mobile nutrient, which is important for osmotic regulation and xylem flow, stomatal movements, and enzyme activation in respiration and photosynthesis (Fromm, 2010). Less mobile nutrients like Ca and Mg are central to the synthesis of cell walls, providing structural support and contributing to enzymatic functions (Fromm, 2010; Garten Jr, 1976). Plants have evolved to acquire nutrients depending on their needs to support their growth rates during various stages of their development (Imsande & Touraine, 1994); therefore, their growth will reflect the balance of nutrients in both the plants and the rooting medium (Garten Jr, 1976; Güsewell, 2004).

In the oil sand mining area of northern Alberta, coversoil material available for upland forest reclamation is comprised mainly of upland surface soil (forest floor material) and peat salvaged prior to mining. Forest floor material is composed of a mixture of the surface leaf litter layer (LFH horizons), A horizon, and potentially a portion of the B horizon from upland forest soils, while peat is the surface horizons of organic soils in lowland bogs and fens. Due to the abundance of natural lowland areas in the mine development footprint and the proportion of lowlands relative to the pre-disturbance condition decreasing (with an increase in uplands) in the reclaimed closure landscape, salvaged peat is commonly used as a coversoil material in upland reclamation. However, its soil chemical and physical characteristics differ from native upland forest floor materials (Hahn & Quideau, 2013; Jamro et al., 2014; Mackenzie & Naeth, 2010; Rowland et al., 2009).

Peat accumulation in bogs and fens is the result of slow organic matter decomposition rates caused by cold temperatures, prolonged water saturation, and anaerobic conditions, resulting in the accumulation of organic material. (Aerts et al., 1999). However, when used as coversoil on an upland site, which is an aerobic environment with warmer soil temperatures, there is potential for the organic material of peat to decompose and initiate nutrient cycling processes that release important macronutrients like N and S for plant uptake (Kong et al., 1980). Other macronutrients, such as P and K, have been found to be limiting in these organic soils (Brown & Naeth, 2014; Howell et al., 2016); therefore, the weathering rate of the underlying subsoil materials may play an important role in the availability of these nutrients (Quideau et al., 2013, 2017; Smith et al., 2011). Selective salvage and placement of subsoil materials that have horizons with varying degrees of weathering at different depths may have an effect on the availability of mineral nutrients on reclamation sites (Barnes et al., 2018). An alternative approach is to salvage subsoils of different types and depths in a single lift, blending the horizons together to produce a homogenized material used for subsoil reconstruction (Naeth et al., 2013). This strategy simplifies the soil salvage operation and can reduce the disturbance if stockpiling is required; however, it can dilute the nutrient concentrations normally supplied by the upper weathered horizons that were near the soil surface, and potentially decrease the availability of P and K for tree uptake and growth (Jung et al., 2014; Ojekanmi & Chang, 2014).

Fertilization is a commonly used method for amending nutrient deficiencies in reclaimed soils, but it has produced varying levels of success. Many field-based studies are conducted on young reclamation sites that are dominated by bare soil materials with low native vegetation cover, which provides a substrate for other colonizing species to inhabit (Pinno and Errington, 2015; Rowland et al., 2009; Sloan and Jacobs, 2013). When developing a fertilizer prescription that specifically targets the planted tree seedlings, a nutrient mixture containing proportions of all macronutrients and some micronutrients is often the easiest approach to ensure the different nutrient requirements of each species are supplemented, especially when a variety of tree species are considered (Chapin III et al., 1986). However, the use of multi-nutrient fertilizers can introduce additional challenges by inducing a strong response from unwanted vegetation, particularly when broadcast applications are used on the bare reclaimed soils, rendering the fertilizer application ineffective (Pinno & Errington, 2015; Pokharel et al., 2017; Schott et al., 2016; Sloan & Jacobs, 2013; van den Driessche et al., 2005).

Nitrogen applied in the form of nitrate (NO_3) or ammonium (NH_4) is often the key nutrient driving competition from colonizing vegetation (Chang & Preston, 2011; Ramsey et al., 2003), especially when applied in combination with P and K (Knecht & Göransson, 2004). When treating nutrient limitations in peat materials, N is often less limiting than P and K, because the high N pool that is retained in the soil organic matter is released through N mineralization as it decomposes (Brown & Naeth, 2014; Hemstock et al., 2009; MacKenzie & Quideau, 2012; McMillan et al., 2007; Quideau et al., 2017). Howsever, if the peat coversoil and mineral subsoil have low available P and K, it is these nutrients that may ultimately control tree seedling growth and may need to be amended (Foster & Bhatti, 2006; Howell et al., 2016; Lanoue, 2003). This study explores whether a targeted application of individual macronutrients rather than a combination of nutrients could: 1) reduce nutrient deficiencies on this coversoil material and improve the growth response of the targeted tree seedlings, while 2) minimizing the competitive response of colonizing species that often render an early application of broad spectrum fertilizer ineffective.

3.2 Methodology

3.2.1 Study Site

The Aurora Soil Capping Study (ASCS) is a large-scale reclamation experiment approximately 36 hectares in size, located at the Syncrude Aurora North Mine lease, about 80km north of Fort McMurray, Alberta, Canada (57°20’N, 111°31’W). The site is located within the central mixed-wood natural subregion, which is characterized by a mixture of forested uplands and wetlands (e.g. bogs, fens and marshes). Mixed stands of trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* Moench.) are often found growing on

Luvisolic soils, while jack pine (*Pinus banksiana* Lamb.) is the dominant species (trembling aspen and white spruce to a lesser degree) on Brunisolic soils (Natural Regions Committee, 2006). Lowland bogs and fens are dominated by black spruce (*Picea mariana* Mill.) and tamarack (*Larix laricina* (Du Roi) K. Koch) tree species that have developed on poorly drained Organic and Gleysolic soils (Natural Regions Committee, 2006). Growing season (May-September) climate normals (1981-2010) for the area have an average daily temperature of 13.4°C and total precipitation of 284.3mm (Government of Canada, 2019b). At the ASCS, average daily temperatures in 2017 and 2018 (May-August) were 16.9°C and 16.5°C, respectively. Total growing season precipitation was 191.8mm in 2017 and 240.3mm in 2018.

3.2.2 Experimental Design

The ASCS is a research trial on an overburden dump that contains material with naturally occurring petroleum hydrocarbons referred to as lean oil sand. Thirteen different soil cover treatments were randomly assigned across the overburden, which ranged in the type of coversoil and subsoil materials and their placement depths. For this fertilizer study, soil treatments containing a 30cm layer of peat coversoil material underlain by two types of deeply salvaged and homogenized subsoil materials (i.e. 30cm of Subsoil BC and 120cm of Subsoil C) were selected (Figure 3-1). The peat was salvaged to the depth of mineral soil contact (up to three to four meters in thickness) from a lowland black spruce and tamarack dominated forest. The subsoil materials were salvaged from a local upland site dominated by Brunisolic soils and included a subsoil BC material that was salvaged between 50 and 100cm, which are generally comprised of the B, BC and C horizons, and a subsoil C material that was salvaged from a depth of 15 to 250cm, which generally encompasses the Bm, B, and C horizons (Figure 3-1). For additional information on the ASCS field design, the reconstructed soil materials, and their profile configurations, see section 2.2.2.

All soil cover treatments were 1ha in size and replicated three times. Tree plots (25m × 25m) were established within each soil cover replicate and planted at a density of 10,000 stems per hectare in 2012 with a single tree species of either trembling aspen, jack pine, or white spruce. Tree seedlings at the ASCS were approaching six years of age when the fertilizer study was implemented (i.e. 2017), which provided an opportunity to see how seedlings with established root systems would respond to fertilizer application on reconstructed soil materials. Within each tree plot, ten smaller fertilizer plots (3m × 3m) containing nine trees were equally spaced and positioned to ensure a minimum distance of 5m between fertilizer plots (Figure 3-1). Since this was a short-term study and the root length of trees in these soil materials did not exceed a root radius of 3.5m for each species (Bockstette, 2017), it was assumed that each fertilizer plot could be considered an independent replicate. The following five fertilizer treatments were assigned to the 3m × 3m fertilizer plots and each fertilizer treatment was replicated twice within each 25m × 25m tree plot: control (no fertilizer), NPK (Nitrogen-Phosphorus-Potassium), PK (Phosphorus-Potassium), P (Phosphorus), and K (Potassium) (Figure 3-1). Fertilizers were composed of three pure chemical compounds that included ammonium nitrate (N), calcium phosphate (P), and potassium sulfate (K); these compounds were selected to ensure that no other macro- or micro-nutrients were added and only N, P, and K were targeted. However, the calcium and sulfate in the P and K fertilizers were considered an exception because the potential confounding effects from their addition were deemed low given the high levels of these nutrients already present in the soil materials (Table 3-1). Granular fertilizers were dissolved in four litres of tap water per fertilizer plot to ensure the nutrients were readily available for trees upon application. Trees were fertilized once in early June 2017 with a dosage equivalent to $250kg\cdot ha^{-1}$ of 10N-30P-20K, which is the same application rate used in a greenhouse study reported by Pinno et al. (2012a) that tested similar reclamation materials near the ASCS study. The NPK treatment received 10-30-20, the PK received 0-30-20, the P received 0-30-0, and the K received 0-0-20 for a per nutrient equivalent of $25kgN\cdot ha^{-1}$, $75kgP\cdot ha^{-1}$, and $50kgK\cdot ha^{-1}$.

3.2.3 Measurements

In May 2017 and prior to fertilizer application, soil samples of the peat coversoil and mineral subsoil materials were taken from the center of each 25m × 25m tree plot, and in 2018 the peat coversoil layer from each 3m × 3m fertilizer plot was sampled. In both years, all soil samples were analyzed for salinity characteristics and plant available nutrients. A saturated paste was made from each soil sample and vacuum filtered to remove the extract; thereafter, the extract was used to measure pH and EC with a pH/EC meter and analyzed by inductively coupled plasma-optical emission spectroscopy (ICP-OES) for Na, Ca, and Mg concentrations, which were later used to calculate SAR (Natural Resources Analytical Laboratory (NRAL), University of Alberta). NO_3^- and NH_4^+ were extracted using KCl and measured by a Thermo Fisher Gallery Beermaster Plus (Thermo Fisher Scientific, Waltham, USA), while all other nutrients were extracted from saturated paste followed by ICP-OES (NRAL, University of Alberta). Instrumentation installed after the initial construction of the ASCS to monitor vadose zone water dynamics and soil temperature were used for the 2017 and 2018 growing seasons in this study, and daily means from May through August were averaged to determine the average growing season soil volumetric water content (VWC) and temperature. Time domain reflectometry (TDR) sensors (Model 616, Campbell Scientific) were used to monitor in situ water content, and thermal conductivity sensors (Model 229, Campbell Scientific) were used to monitor in situ temperatures at four depths below the soil surface (i.e. 5cm, 15cm, 25cm, 35cm).

Trees within each fertilizer plot were measured three times throughout the study for their height (from ground to bud tip) and root collar diameter (RCD; at ground level): May 2017 (prior to fertilization and spring flush; equivalent to 2016 fall height), August 2017 (first year measurement after fertilizer application), and August 2018 (second year measurement). In order to make comparisons among tree species and their responses to the fertilizer treatments, relative height and RCD in 2017 and 2018 were calculated in relation to the 2016 measurements (e.g., 2017height/2016height and 2018height/2016height). Foliar samples were collected in August 2017 and July 2018 to assess foliar nutrient concentrations. Leaves or needles were taken from three trees and pooled per fertilizer plot. Samples were immediately cold stored in the field after collection and later frozen for future processing; thereafter, samples were dried at 100°C for one hour and then at 70°C to constant weight, ground with a Wiley mill, sorted through a 0.4mm mesh filter, and sent for nutrient analysis to assess for N, P, K, S, Ca, and Mg (NRAL, University of Alberta). N was measured by combustion, while all other nutrients were measured by microwave digestion followed by ICP-OES. Foliar nutrient concentrations were used to calculate N:P, N:K, and N:S ratios for each species and fertilizer treatment. To assess the levels of competition for nutrients between tree seedlings and colonizing vegetation, surveys of total vegetation cover were conducted in each fertilizer plot using a 1m × 1m quadrat in August of 2017 and 2018.

3.2.4 Statistical Analysis

All analyses were executed using R software, v 3.4.3, 65 bit (R Core Team, 2018a). Soil VWC and temperature was averaged to the 1ha soil cover level, soil chemistry data from 2017 was averaged to the 25m × 25m tree plot level, and all other data (i.e. 2018 peat chemistry data, tree height and RCD, foliar nutrient concentrations and ratios, vegetation cover) was averaged to the fertilizer plot level. Model residuals were tested for normality using the Shapiro-Wilk test from the R *stats* package (v 3.6.0; R Core Team, 2018b) and homogeneity of variance using Levene's test in the R *car* package (v 3.0-0; Fox et al., 2018); when data did not meet assumptions of normality or homogeneity, they were adjusted using transformations, or analyzed using a permutational test using the R *lmPerm* package (v 2.1.0; Wheeler et al., 2016) if transformations were inadequate. Due to the low replication necessitated by logistics of this large operational study, a $p \leq 0.1$ was used in all analyses to reduce the risk of Type II error.

Differences in soil nutrients and salinity characteristics between the peat and subsoil materials in 2017 and fertilizer treatments in 2018 were analyzed in a one-way ANOVA. Soil VWC and temperature were compared at each soil depth in a repeated measures ANOVA with soil cover treatment and year as the fixed effects. Comparisons of total tree height and RCD in May 2017 (i.e. 2016 height), August 2017, and August 2018, as well as total vegetation cover, were compared between fertilizer treatments and years using a repeated measures ANOVA. Relative height and RCD were compared among fertilizer treatments and tree species within each soil cover treatment and year in a two-way ANOVA. Foliar N:P, N:K, and N:S ratios of each species in 2018 were compared between fertilizer treatments within each soil cover treatment using a one-way ANOVA. When a significant effect or an interaction was detected, the Fishers LSD test from the *agricolae* package was used to conduct post-hoc pairwise comparisons ($\alpha \leq 0.1$; v 1.2-8; de Mendiburu, 2017).

3.3 Results

3.3.1 Tree Responses

Compared among all species, the strongest response to the targeted fertilizer application was observed in trembling aspen (Fertilizer × Species: $p = 0.004$), where the relative height of aspen growing in the Peat/C was 26% higher in the P treatment compared to the control in 2018 (Figure 3-2). This corresponds to absolute growth that was 28.1cm greater than the control (15.8cm) ($p = 0.05$; Table B-2). Relative RCD of aspen in the same soil cover was at least 5% higher in the NPK, PK, and K treatments in 2017 and 10% higher in the NPK, P and K treatments in 2018 when compared to the control (2017: $p = 0.07$; 2018: $p = 0.06$; Figure 3-3). In the Peat/BC soil cover, only relative RCD responded to the NPK and PK fertilizer treatments and were 10% higher than the control in 2018 ($p = 0.08$; Figure 3-3).

Foliar N concentrations of aspen leaf samples from the Peat/C soil cover in 2017 increased in the NPK and K treatments compared to the controls ($p = 0.01$; Table B-3). In the Peat/BC soil cover, foliar N in the NPK, PK, and P treatments from 2018 had decreased below the concentrations observed in the controls and the K treatment ($p = 0.02$; Table B-3). Foliar K concentrations in the Peat/C soil cover increased in the K treatment in 2017 ($p = 0.08$; Table B-3). In the Peat/BC soil cover, foliar K increased in the PK and K treatments compared to the controls in 2017, and by 2018, K concentrations were higher in the NPK and PK treatments ($p = 0.02$ for both years; Table B-3). Foliar N:P ratios in aspen decreased in response to all P fertilizer treatments on the Peat/BC soil cover ($p = 0.001$; Table 3-2). Similarly, N:K ratios decreased in all P fertilizer treatments in the Peat/BC ($p = 0.03$), while a decrease was only observed in the P treatment on Peat/C ($p = 0.06$; Table 3-2). Interestingly, N:K ratios in the K treatment did not change relative to the control on either soil cover (Table 3-2).

Relative height of jack pine grown on Peat/C was the only growth parameter that marginally responded to the NPK treatment in 2017 ($p = 0.08$; Figure 3-2). Absolute height of pine in the Peat/BC soil cover responded to the P and PK treatments in 2018 ($p = 0.02$; Table B-2), where pine growth was 9.3cm and 6.9cm higher in the P and PK treatments, respectively, compared to the control. A similar response was observed in absolute RCD ($p = 0.02$; Table B-2). Foliar K concentrations in the Peat/BC increased in the PK and K treatments in 2018 ($p = 0.01$; Table B-3). Foliar N:P ratios in pine decreased in all P fertilizer treatments in the Peat/BC soil cover ($p = 0.07$; Table 3-2). Foliar N:K ratios of pine grown in the Peat/BC decreased in the PK and K treatments ($p = 0.03$; Table 3-2).

The response of white spruce to fertilizer application was the lowest of the three species, regardless of the soil cover. Absolute height of spruce trees in the Peat/BC was the only growth parameter that responded to the P treatment ($p = 0.002$), where spruce growth was 5.6cm higher than the control in 2018 (Table B-2). Foliar N concentrations of spruce needles grown in Peat/C increased by 27% relative to the control in the NPK treatment in 2017, and this response disappeared by 2018 (Fertilizer × Year: 0.16; Table B-3). In the Peat/BC, foliar N:P ratios decreased in the PK and P treatments compared to the control ($p = 0.002$; Table 3-2). Unlike the first two tree species discussed, foliar N:S in the Peat/BC responded to fertilizer application by increasing in the NPK and P treatments compared to the control ($p = 0.003$; Table 3-2).

3.3.2 Colonizing Vegetation

Total colonizing vegetation cover in 2017 increased in the NPK, PK, and P treatments compared to the control, where cover was higher by 21%, 8%, and 4%, respectively ($p < 0.001$; Figure 3-4). These same response patterns in the NPK continued into the second growing season, however the total cover in the NPK treatment was lower than in the previous year (Fertilizer × Year interaction: $p < 0.001$; Figure 3-4). The response of the colonizing vegetation to the fertilizer application was primarily driven by one species, *Salsola pestifer* A. Nels. (Russian Thistle), an annual species contained in the soil seedbank that can respond strongly to fertilizer applications, particularly containing N (Beckie & Francis, 2010). In our study this species comprised more than 90% of the total cover in all fertilizer treatments for both years (Figure 3-5).

3.3.3 Edaphic and Climatic Factors

The 2017 growing season was drier than 2018 at the ASCS, receiving 191.8 mm of precipitation in 2017 compared to 240.3mm in 2018 (Section 3.2.1). A draw-down in volumetric water content (VWC) to approximately 25% was evident in both soil covers near the end of the 2017 growing season (Figure A-3), which represents the approximate wilting point of plants in pure peat materials (Ojekanmi & Chang, 2014). In 2018, there were two large precipitation events, as noted by the arrows in Figure A-3, that maintained a VWC above 30% throughout the summer. Soil temperatures differed between the two soil covers with increasing depth into the rooting zone, resulting in cooler temperatures in the Peat/BC compared to Peat/C by approximately 3°C at the lowest measurement depth ($p < 0.001$ for depths 15cm, 25cm, and 35cm in 2017; $p < 0.001$ for 35cm depth in 2018; Table B-4). These temperature differences partially coincided with a higher soil VWC with increasing depth, where VWC was marginally higher in the Peat/BC compared to Peat/C ($p = 0.07$ at 35cm depth in 2018; Table B-4).

The soils sampled in 2017 reported a slightly alkaline pH of approximately 8 in all soil materials (Table 3-1). Differences in EC were found among the soil materials, where the peat in each soil treatment had higher EC levels than their underlying subsoils ($p < 0.001$); however, all soil materials were classified as non-saline (EC < $2dS \cdot m^{-1}$; Table 3-1). Sodium Adsorption Ratios (SAR) were all under two, which is considered non-sodic, and did not differ among the soil materials ($p > 0.1$; Table 3-1). Plant available nutrients (except P) were generally higher in the peat materials compared to the subsoils, while the peat coversoil placed over the subsoil BC material had higher levels of NO_3, S, Ca, and Mg than the peat on subsoil C ($p < 0.001$ for all; Table 3-1). Phosphorus concentrations were low and undetectable in several subsamples used in the analysis (Table 3-1), and these levels were comparatively lower than levels found in the surface litter layer (LFH horizon) and Bm horizons of natural upland soils that were sampled within the same locale as the soils of the ASCS (32-40mg/kg of P; Table B-5). Similarly, K concentrations were low when compared to the natural upland soils (387 mg/kg of K; Table B-5), but K concentrations were higher and more available than P in the ASCS soil materials (Table 3-1).

Measurements of SAR, EC, and pH in the peat coversoil sampled in August 2018 did not change in response to fertilizer application ($p > 0.1$ for all; Table 3-3). Similarly, all plant available nutrients, except for NO_3 and K, did not differ across the fertilizer treatments. Available K was at least 170% higher in the NPK, PK, and K treatments relative to the control ($p < 0.001$), indicating that K fertilizer infiltrated at least 15cm below the soil surface where the soil samples were taken (Table 3-3). However, P was not detectable at the same sample depth of 15cm (Table 3-3). Available NO_3 was 44% higher in the K treatments relative to the control in the peat placed over the subsoil C material ($p = 0.05$).

3.4 Discussion

A targeted fertilizer application produced different responses among trembling aspen, jack pine, and white spruce, and the strength of these responses appear to be strongly influenced by the nutritional requirements of the targeted species, the chemistry of the peat layer, the subsoil treatment (i.e. type and thickness), and the environmental conditions of each growing season. Analysis of soil nutrient availability prior to fertilization reported low levels of K, and at times, undetectable levels of P in all peat and subsoil materials (Table 3-1), suggesting a limited availability of these nutrients for plant uptake compared to levels found in natural upland forest soils (Table B-5, Foster & Bhatti, 2006; Lanoue, 2003). Since the most limiting nutrient(s) will likely impact plant growth the most (Liebig, 1840), we expected to have the greatest increase in plant response to an addition of P and/or K in the three tree species tested. In our study, the strongest response to fertilization was observed in aspen grown in the Peat/C soil cover, particularly when only P was applied, while both conifers responded minimally to any of the fertilizer treatments (Figure 3-2). The root systems of the planted seedlings had been established for five growing seasons at the time of fertilizer application, and we expected that the efficacy of nutrient uptake from these expanding root systems would be greater and height growth rates would significantly improve, particularly for aspen which is known for significantly allocating more carbon to root system development during early establishment (Landhäusser & Lieffers, 2001; Landhäusser et al., 2012b). While growth rates of aspen in the P only treatment in the Peat/C reached levels that were similar to those in aspen growing in salvaged forest floor material (27.9cm per year, section 2.3.1), the same was not observed in the P only treatment on the Peat/BC coversoil, and when considering neither conifer species responded as strongly as expected to the targeted fertilizer treatments, the varied responses suggest there were other variables that might have limited growth in these reconstructed soils.

The abundance of nutrients and their relation to each other (i.e. their ratios) in the peat material might have influenced the internal nutrient balance within the trees and subsequently their physiological processes and growth (Diem & Godbold, 1993; Garten Jr, 1976). Phosphorus is particularly important for plant growth given its major role in forming nucleic acids, phospholipids and adenosine triphosphate (Schachtman et al., 1998), and this nutrient can be the most limiting to tree growth, particularly in the fast growing aspen (Burns & Honkala, 1990; Chapin III et al., 1983; Chen et al., 1998). Foliar P concentrations sampled in all three species from both soil covers were below the optimal levels published for related *Populus* species (<0.33%; Hansen, 1994; Kopinga & Van den Burg, 1995), white spruce (<0.14%; Allen, 1987; Ballard & Carter, 1986), and the closely related lodgepole pine (<0.16%; Weetman et al., 1985), supporting our prediction that P was a limiting nutrient for trees grown in these soil materials. The addition of P improved this limitation for aspen in the Peat/C and resulted in greater growth (Figure 3-2); however, the aspen grown in the Peat/BC only showed a response when exploring the foliar N:P ratio and not growth

(Table 3-2). Foliar N:P ratios of aspen in the controls were considerably higher than 15 on both soil covers (Table 3-2), where a value of 15 indicates an approximate ratio where N and P are considered balanced within the plant (Güsewell et al., 2003). Ratios higher than this value indicate a deficiency in P, and in 2018 P fertilization significantly lowered the foliar N:P ratio of aspen in the Peat/BC closer to this balance value of 15 (Table 3-2).

The addition of P had the same effect on the foliar N:P ratios of both conifer species in the Peat/BC; however, P treatments lowered the ratios below the value of 15, potentially indicating a need for more N (Table 3-2). This was further supported by the low foliar N concentrations that were below the suggested optimum level of 1.55% for both conifer species (Table B-3; Allan, 1987; Ballard & Carter, 1986, Weetman et al., 1985), suggesting N might have been more limiting for pine and spruce than P and may be partly responsible for the lack of responses in the conifers. Although NPK was applied in this study, the application rate of nitrogen (25kg/ha) was low compared to other operational application rates (85kg/ha to 200kg/ha of N), and P and K (the focus of this study) were applied proportionally at a higher rate than N (Lanoue, 2003; Pinno & Errington, 2015; Rowland et al., 2009). Furthermore, Pine and spruce will preferentially use ammonium over nitrate (Duan et al. , 2015; Kronzucker et al., 1997; Lavoie et al., 1992), and given the higher availability of nitrate compared to ammonium in the peat prior to fertilization, it is likely ammonium was the limiting form of N for the conifer species in the study and a higher application rate of this nutrient was required.

Potassium is more mobile than P (Chapin III et al., 1986), and trees are able to regulate the uptake of K when other nutrients like N and P are less available (Clarkson, 1985). Targeting P rather than K may have improved the internal balance of K as observed in the N:K ratios of aspen and to a lesser extent in jack pine, suggesting there was an increase in K uptake relative to N within the foliar pool as P became more available after fertilization (Table 3-2). Furthermore, K availability was likely not as limiting as originally predicted from the soil samples in 2017 (Table 3-1) based on the foliar K concentrations that were within values considered optimal for each species (aspen: 1.6% (Hansen, 1994, Kopinga and Van den Burg, 1995); pine and spruce: 0.5% (Allen, 1987, Ballard & Carter, 1986, Weetman et al., 1985); Table B-3).

Soil nutrient concentrations of S, Ca, and Mg were substantially higher in the soils materials compared to the levels found in natural upland sites (Table 3-1; Table B-5), which is common for reclaimed soils in the region (Howat, 2000; Howell et al., 2016). These nutrients play an important role in plant metabolism, photosynthesis, and cell structure (Fromm, 2010; Garten Jr, 1976); however, when the abundance of these nutrients is higher than N, P, and K, it could create nutrient imbalances that may negatively impact growth (Diem & Godbold, 1993). Phosphorus fertilization increased the foliar N:S ratios of spruce, suggesting the increased availability of P improved the uptake of N in relation to the high concentrations of S in the peat (Table 3-2). Nutrients like Ca are considered less mobile than S and are unregulated during uptake, which can lead to an accumulation of Ca within the tree (Knecht & Göransson, 2004). Foliar concentrations of Ca in our study supports this accumulation, which were higher than optimal levels in aspen (0.63%, Hansen, 1994) and the conifer species (0.1-0.2%, Ballard and Carter, 1986, Weetman et al., 1985) on both soil covers.

An important consideration in this study that will require further investigation is the interaction between the alkalinity (pH 8) and highly available Ca in the peat materials (Table 3-1). This is likely a legacy effect from the salvage site where the underlying mineral soil was high in calcium carbonate. Studies on the effect of high pH and Ca availability have been linked to reduced water uptake, and with that transpiration and photosynthesis, in pH sensitive species like aspen and pine, while late successional species like spruce are more tolerable of these conditions (Zhang et al., 2013; Zhang et al., 2015). Furthermore, phosphorus sorption in organic matter is positively related to pH, because in high pH soils the organic acids, which inhibit the sorption of P, decrease (Guppy et al., 2005). As a result, the competition for sorption sites decrease and cations, particularly Ca, can attach to the P ions and reduce their availability for plant use (Bell & Black, 1970; Bolan et al., 1988; Tunesi et al., 1999; Vetterlein et al., 1999). This mechanism is supported by our observation that P levels did not increase 15cm below the peat surface in 2018, while the added K was clearly present and detectable at that same depth. Furthermore, Ca concentrations were substantially higher in the peat placed over the subsoil BC material, which may further explain why overall tree growth was not responsive to P additions compared to the Peat/C which had lower Ca levels in the peat (Table 3-1; Figure 3-2).

Soil moisture availability in the first growing season may also partly explain the limited growth responses observed in 2017. Soil water content steadily decreased following fertilizer application in early June, a result of the low precipitation throughout the 2017 growing season (Figure A-3). Consequently, this may have slowed the infiltration rate of the applied nutrients, and combined with immobilization, could have reduced the rate of nutrient uptake by the tree roots. The weak growth responses observed in the first growing season corresponded with these conditions and has been observed in other studies (Fageria, 2013; Kreuzwieser & Gessler, 2010, Man & Greenway, 2013; van den Driessche et al., 2005, 2003). However climatic conditions improved by the second year when the ASCS received higher total rainfall and a spring snow melt that would have assisted with infiltration of the nutrients at the beginning of that year when trees were emerging from winter dormancy (Figure 3-2). Evidence of this deeper infiltration is supported by the elevated K levels in all K fertilized treatments that indicate K had infiltrated to the root zone by 2018 (Table 3-3).

Cool soil conditions created by the insulative properties of the 30cm layer of peat coversoil combined with high soil moisture in the lower peat layers may also explain some of the limited growth observed in the Peat/BC fertilizer treatments. One difference between the two soil covers is their capping depths (150cm for Peat/C vs. 60cm for Peat/BC; Figure 3-1). A hydrological boundary along the contact between the coarse subsoils and finer textured and hydrocarbon-containing overburden (Table 2.1) may have slowed infiltration at this interface and increased the water content in BC subsoil layer (Huang et al., 2013; Zettl et al., 2011). Since this interface is closer to the surface in the Peat/BC compared to the Peat/C, its effect on soil moisture and temperature becomes more apparent at a shallower depth in the Peat/BC (Table B-4). Higher water content in insulative materials like peat may create cool soil conditions that slow the uptake of water and nutrients (Landhäusser et al., 2003; Wan et al., 1999; Wolken et al., 2011; Zhao & Si, 2019), particularly in early successional species like aspen and pine that prefer temperatures above 15°C for optimal growth. Given soil temperatures below the 5cm depth were less than 15°C, the cooler temperatures within the peat may have been more limiting to tree growth than soil nutrition in the Peat/BC, reducing the ability of the trees to respond to targeted fertilization.

Lastly, the strong response of the competing colonizing vegetation to the application of nutrients could have also had an impact on tree growth (Figure 3-4). This is a common response when broadcast applications are used on reclaimed soils that are often bare and devoid of native vegetation (Pinno & Errington, 2015; Pokharel et al., 2017; Robinson et al., 2001; Sloan & Jacobs, 2013; van den Driessche et al., 2005). Peat materials used in reclamation generally lack a source of propagules associated with natural forest upland areas, resulting in a vegetation cover dominated by non-native species that have migrated onto the site (Brown & Naeth, 2014; Jones & Landhäusser, 2018; Mackenzie & Naeth, 2010). In this study, fertilized plots were dominated by a weedy early colonizer known as *Salsola pestifer* (Figure 3-5), which was already present on the ASCS prior to fertilization (Jones & Landhäusser, 2018). Germination of this annual species occurs when soil temperatures increase above 15°C (Crompton & Bassett, 1985), and temperatures reached this threshold in the upper layers of the peat by the end of May in 2017, which was shortly before the fertilizer treatments were applied. Considering the low rainfall of that year, most of the fertilizer likely remained at the soil surface until higher precipitation was received the following year. *Salsola pestifer* was likely able to utilize the liquid fertilizer that remained near the soil surface, and as a result, a significant portion of the applied nutrients intended for the trees was picked up by *S. pestifer* within the first year, particularly in the NPK treatment where N appears to be the strongest driver of the growth in this species. A targeted fertilization with P and K successfully limited the competition of this species, which highlights the possibility of targeting individual nutrients during broadcast applications and limiting N application that would otherwise support the establishment of ruderal species adapted to environments requiring strong competition for essential resources (Grime, 1977).

The intent of targeted fertilization in forest reclamation is to improve nutrient-specific deficiencies in the soil necessary for the establishment and growth of planted species that have relatively low nutrient requirements, particularly for N. In that case, the application of the nutrients could limit the development of competing ruderal vegetation cover that requires high resource availability. Evidence collected in this study suggests that the success of this method is dependent on the type of species that is targeted, the type of reconstructed materials, and the soil conditions at the time of fertilizer application. In this study the targeted fertilization of peat successfully increased the growth rates of aspen similar to those observed in more productive mineral coversoils; however, this response was not observed in pine and spruce most likely due to their own set of unique nutrient requirements. When considering the application of nutrients in a boreal mixedwood scenario where both early and late successional tree species are planted together, it may be important to initially target the nutrient application to the fast-growing deciduous species that have extensive root systems capable of readily using the applied nutrients, which will increase the leaf litter output provided by these trees over time and improve the nutrient cycling processes and N availability for later successional species such as white spruce.

It is equally important to consider the limitations associated with the type of soil materials on site and their condition prior to fertilization because these factors may limit nutrient availability, even when these nutrients are present in the soil. The peat material used as the coversoil created temperature and chemical limitations that likely reduced the availability of the applied fertilizers. Higher application rates could have possibly overcome these soil limitations; however, improving drainage in the peat layer during reconstruction could have also mediated these limitations and improved nutrient availability by lowering the water content in the lower peat layers and allowing soil temperatures to increase to more optimal levels for root growth. Improving drainage could also accelerate the removal of calcium carbonate from the peat, allowing the pH to decrease over time. Options that could be used to accomplish these conditions include the incorporation of salvaged upland mineral soil material with the peat during soil placement, and/or by increasing the total placement depth of the soil cover to create distance between the peat layer and the underlying hydrological barriers, assuming there is additional material available for use. The knowledge gained from this study will contribute to the ongoing development of forest reclamation best practices for the Boreal region, increasing afforestation success by recognizing and carefully considering limiting site factors.

3.5 Tables

Table 3-1: Sodium Adsorption Ratio (SAR), Electrical Conductivity (EC), pH, and plant available nutrients (±SE) in the Peat and subsoil materials sampled in 2017. Letters indicate statistically significant differences between means in the soil (α ≤ 0.1; n=9), and if letters are absent, this indicates there were no significant differences between means. All plant available nutrients were logarithmically transformed prior to analysis.

	SAR	EC ($dS \cdot m^{-1}$)	pH	Plant Available Nutrients ($mg \cdot kg^{-1}$)						
				NO_3	NH_4	P	K	S	Ca	Mg
Peat	0.23	0.88	8.22	18.06	7.13	0.15	6.35	172.56	240.56	23.42
	(0.03)	(0.11)^{b}	(0.04)	(3.87)^{a}	(0.50)^{a}	(0.06)	(1.02)^{a}	(33.54)^{b}	(33.43)^{b}	(3.96)^{b}
Subsoil C	0.20	0.51	8.08	0.81	1.17	0.04	1.07	23.08	28.21	2.97
	(0.01)	(0.04)^{c}	(0.13)	(0.08)^{b}	(0.12)^{b}	(0.01)	(0.06)^{c}	(2.75)^{d}	(2.23)^{c}	(0.35)^{c}
Peat	0.27	1.32	8.08	34.2	6.90	0.09	4.19	347.55	400.81	40.19
	(0.07)	(0.17)^{a}	(0.05)	(10.9)^{a}	(0.46)^{a}	(0.04)	(0.50)^{b}	(57.13)^{a}	(57.84)^{a}	(6.69)^{a}
Subsoil BC	0.25	0.68	7.99	1.39	1.39	0.01	0.79	33.70	38.37	4.28
	(0.05)	(0.08)^{bc}	(0.07)	(0.45)^{b}	(0.45)^{b}	(0.01)	(0.07)^{d}	(6.04)^{c}	(5.22)^{c}	(0.62)^{c}

Table 3-2: Foliar N:P, N:K, and N:S ratios (±SE) of trembling aspen, jack pine, and white spruce grown in either Peat over Subsoil C or Peat over Subsoil BC in 2018. Letters indicate statistically significant differences between foliar ratio means in fertilizer treatments within each tree species (α ≤ 0.1; n=6), and if letters are absent, this indicates there were no significant differences between means.

Soil Cover	Ratio Type	Tree Species	Control	NPK	PK	P	K
Peat over Subsoil C	N:P	Trembling Aspen	29.24 (2.29)	26.04 (1.97)	26.60 (2.04)	24.08 (1.72)	30.86 (1.51)
		Jack Pine	11.66 (1.40)	9.23 (1.41)	10.58 (1.60)	9.94 (1.14)	11.34 (1.22)
		White Spruce	9.69 (1.05)	8.94 (1.66)	8.63 (1.52)	10.17 (1.69)	10.70 (2.04)
	N:K	Trembling Aspen	2.45 (0.09)^{ab}	2.43 (0.12)^{abc}	2.36 (0.12)^{bc}	2.21 (0.06)^{c}	2.64 (0.08)^{a}
		Jack Pine	1.79 (0.32)	1.68 (0.23)	1.89 (0.32)	1.84 (0.27)	1.70 (0.27)
		White Spruce	1.42 (0.32)	1.48 (0.39)	1.34 (0.30)	1.59 (0.40)	1.41 (0.36)
	N:S	Trembling Aspen	7.98 (0.27)	8.14 (0.38)	8.26 (0.43)	7.87 (0.32)	8.20 (0.29)
		Jack Pine	8.98 (0.37)	8.74 (0.26)	9.19 (0.18)	9.21 (0.06)	9.03 (0.18)
		White Spruce	8.78 (0.32)	8.59 (0.41)	8.25 (0.27)	9.13 (0.42)	8.24 (0.26)
Peat over Subsoil BC	N:P	Trembling Aspen	34.36 (1.18)^{x}	26.68 (1.72)^{y}	27.33 (1.15)^{y}	27.87 (1.62)^{y}	34.31 (1.81)^{x}
		Jack Pine	15.82 (1.39)^{x}	12.01 (0.94)^{y}	12.25 (0.82)^{y}	11.94 (1.09)^{y}	14.35 (1.13)^{xy}
		White Spruce	11.22 (0.27)^{wx}	10.29 (0.47)^{xy}	8.97 (0.61)^{z}	9.86 (0.68)^{yz}	12.17 (0.43)^{w}
	N:K	Trembling Aspen	2.90 (0.18)^{x}	2.31 (0.18)^{y}	2.18 (0.13)^{y}	2.37 (0.13)^{y}	2.80 (0.12)^{x}
		Jack Pine	2.54 (0.20)^{x}	2.34 (0.16)^{xy}	1.99 (0.09)^{y}	2.26 (0.16)^{xy}	2.12 (0.15)^{y}
		White Spruce	1.18 (0.05)	1.29 (0.09)	1.15 (0.08)	1.30 (0.10)	1.16 (0.06)
	N:S	Trembling Aspen	7.67 (0.47)	7.32 (0.57)	7.07 (0.51)	7.25 (0.73)	8.30 (0.96)
		Jack Pine	9.34 (0.43)	8.98 (0.53)	8.87 (0.33)	8.79 (0.23)	8.92 (0.47)
		White Spruce	10.43 (0.37)^{y}	11.74 (0.54)^{x}	10.80 (0.42)^{xy}	11.71 (0.53)^{x}	10.83 (0.44)^{xy}

Table 3-3: Sodium Adsorption Ratio (SAR), Electrical Conductivity (EC), pH, and plant available nutrients (±SE) sampled from the peat coversoil 15cm below the surface in 2018. Letters indicate statistically significant differences between means in fertilizer treatments within each soil cover ($\alpha \leq 0.1$; n=9), and if letters are absent, this indicates there were no significant differences between means.

Soil Cover	Fertilizer Treatment	SAR	EC ($dS \cdot m^{-1}$)	pH	Plant Available Nutrients ($mg \cdot kg^{-1}$)						
					NO_3	NH_4	P	K	S	Ca	Mg
Peat over Subsoil C	Control	0.24 (0.05)	0.87 (0.13)	7.99 (0.05)	5.7 (0.7)^{bc}	11.0 (0.5)	< 0.015	13.3 (1.5)^{c}	152.9 (44.0)	338.0 (35.6)	34.5 (5.0)
	NPK	0.31 (0.06)	0.97 (0.11)	7.97 (0.03)	7.6 (1.8)^{ab}	11.4 (0.9)	< 0.015	40.1 (3.3)^{a}	203.6 (38.0)	358.2 (29.7)	37.2 (4.1)
	PK	0.29 (0.07)	0.92 (0.15)	8.03 (0.04)	4.3 (0.3)^{c}	10.9 (0.7)	< 0.015	36.4 (3.4)^{ab}	151.1 (48.8)	308.8 (38.7)	31.9 (5.1)
	P	0.27 (0.05)	1.07 (0.09)	8.02 (0.02)	4.9 (0.5)^{c}	12.0 (0.7)	< 0.015	15.1 (1.4)^{c}	232.5 (46.6)	392.5 (58.8)	39.8 (4.7)
	K	0.27 (0.04)	1.05 (0.10)	8.02 (0.02)	8.2 (1.3)^{a}	12.2 (1.1)	< 0.015	31.4 (4.1)^{b}	214.8 (44.5)	381.6 (33.2)	38.3 (3.7)
Peat over Subsoil BC	Control	0.19 (0.03)	1.18 (0.24)	7.91 (0.05)	5.6 (1.0)	10.7 (0.8)	< 0.015	13.5 (2.4)^{y}	377.0 (113.0)	572.5 (101.4)	67.3 (21.7)
	NPK	0.20 (0.03)	1.01 (0.14)	7.87 (0.04)	6.1 (1.1)	10.2 (0.8)	< 0.015	36.7 (4.1)^{x}	284.5 (85.4)	456.8 (92.2)	46.1 (8.7)
	PK	0.24 (0.06)	1.00 (0.09)	7.94 (0.04)	9.5 (2.8)	9.9 (0.6)	< 0.015	43.1 (8.6)^{x}	295.9 (74.6)	452.5 (80.5)	50.1 (10.2)
	P	0.19 (0.04)	1.08 (0.21)	7.92 (0.06)	9.6 (2.5)	11.3 (0.9)	< 0.015	14.9 (5.7)^{y}	356.9 (139.4)	558.6 (151.3)	51.9 (15.0)
	K	0.21 (0.03)	1.24 (0.22)	7.93 (0.03)	4.3 (0.5)	10.0 (0.6)	< 0.015	37.7 (4.1)^{x}	353.7 (120.2)	557.2 (132.7)	51.0 (10.7)

3.6 Figures

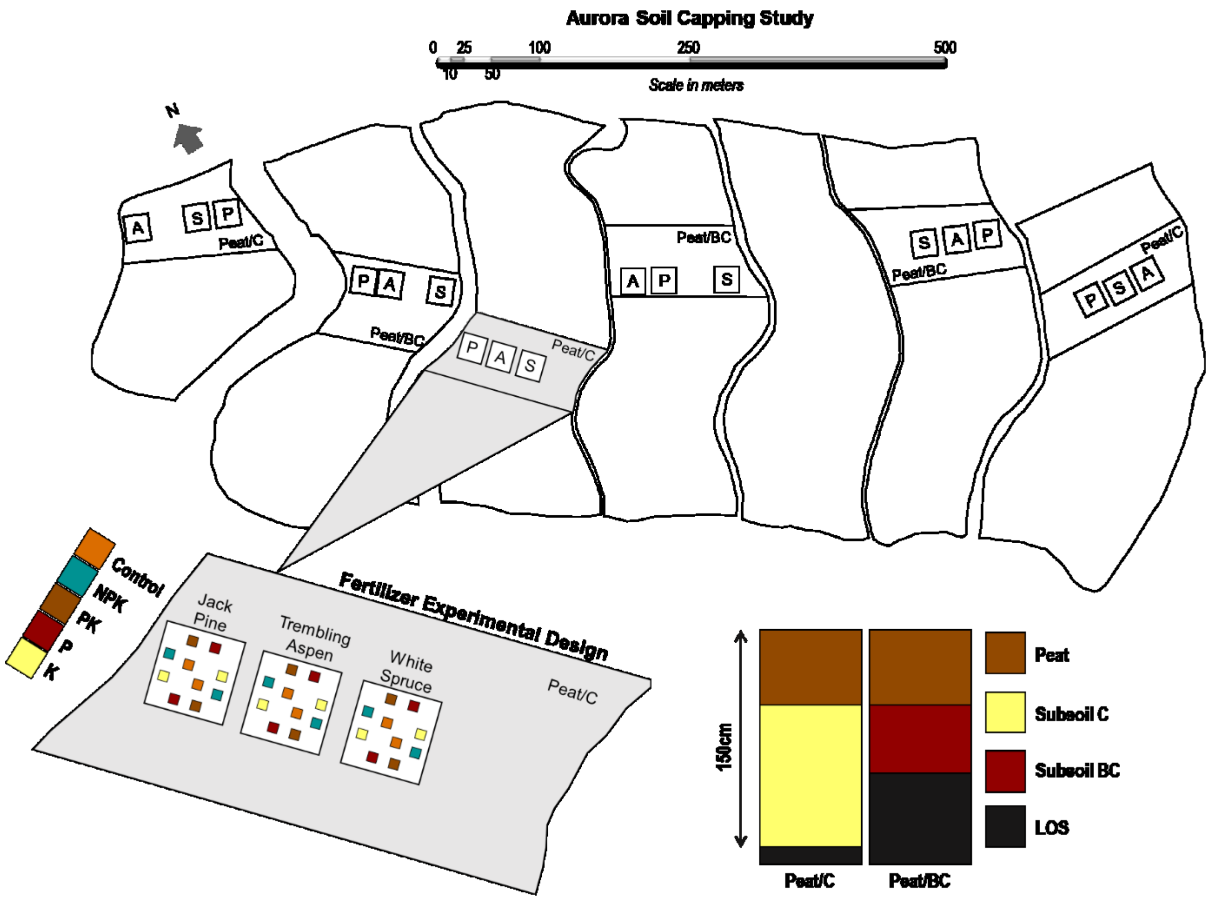

Figure 3-1: Three single species tree plots planted with trembling aspen, jack pine, or white spruce were grown on two different soil covers from 2012 to 2017 at the Aurora Soil Capping Study: 150cm of Peat over Subsoil C and 60cm of Peat over Subsoil BC. Five fertilizer treatments were replicated twice within each 25m × 25m tree plot and applied in 2017: Control (no fertilizer), Nitrogen-Phosphorus-Potassium (NPK), Phosphorus-Potassium (PK), Phosphorus (P), and Potassium (K).

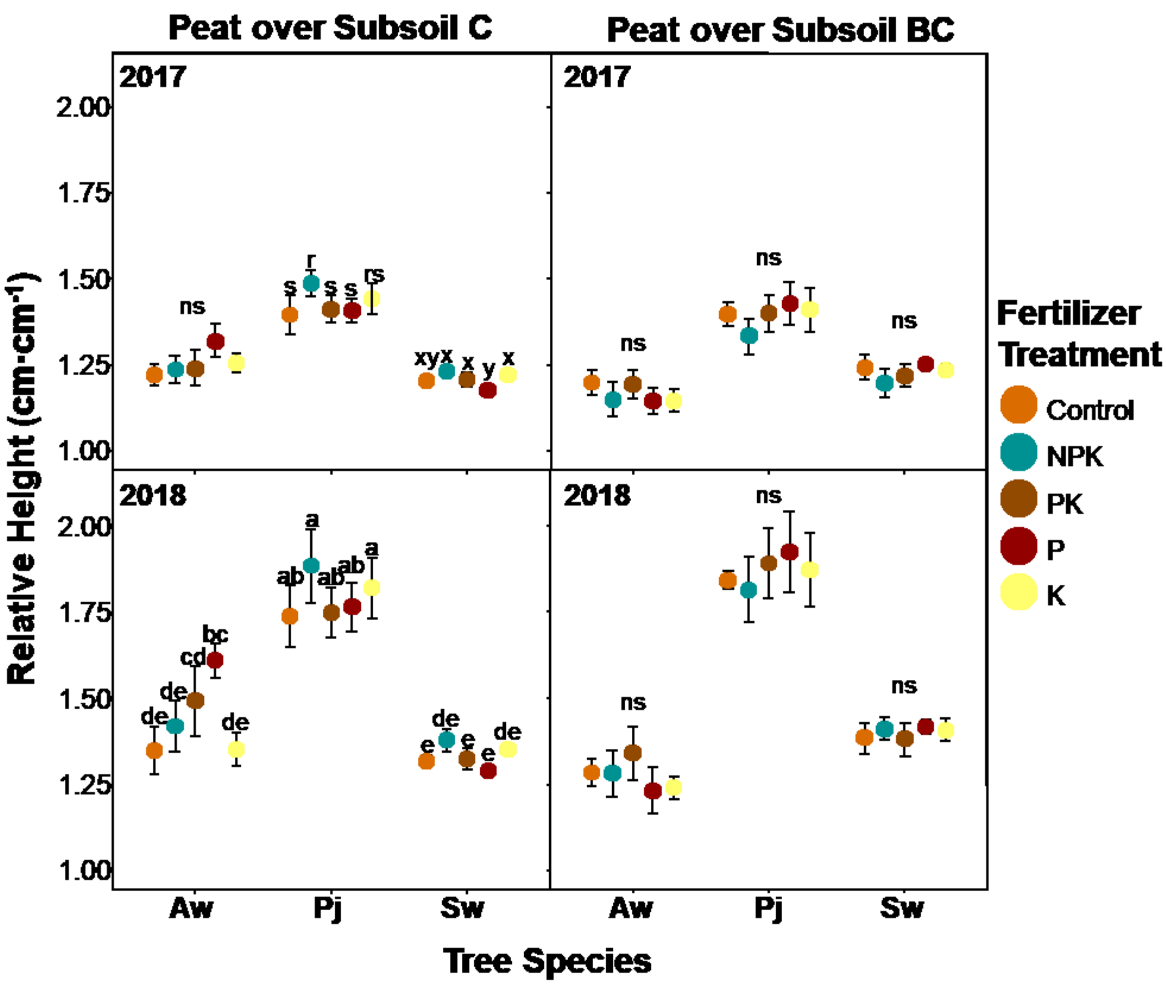

Figure 3-2: Relative height (±SE) of trembling aspen (Aw), jack pine (Pj), and white spruce (Sw) grown in Peat over Subsoil C (left panels) and Peat over Subsoil BC (right panels) in 2017 and 2018. The effect of fertilizer, tree species, and their interaction was tested within each soil group and year. Letters indicate statistically significant differences between means in fertilizer treatments (α≤0.1, n=6). If a significant interaction was found, pairwise comparisons were conducted across all fertilizer treatment and tree species combinations.

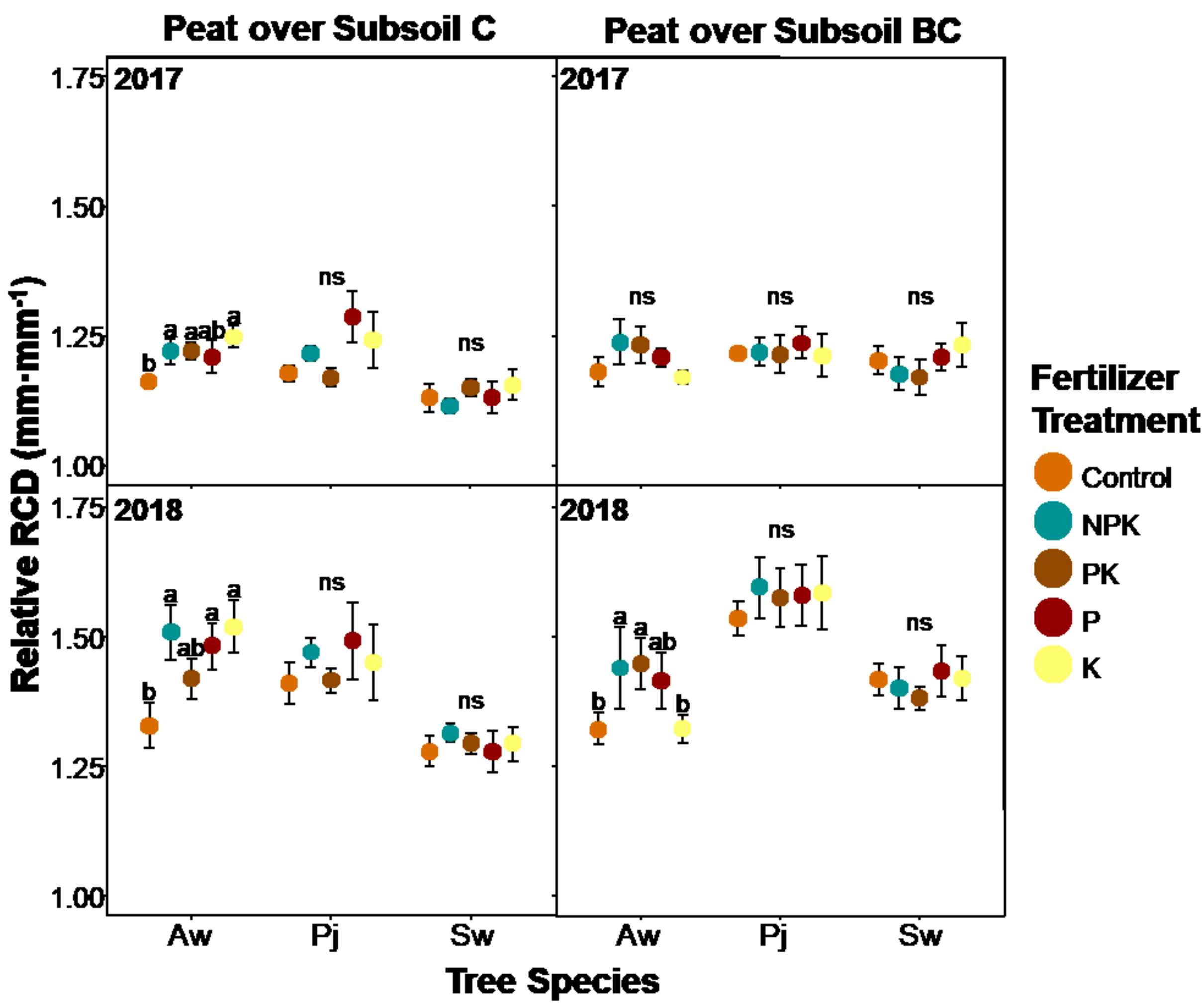

Figure 3-3: Relative root collar diameter (RCD) (±SE) of trembling aspen (Aw), jack pine (Pj), and white spruce (Sw) grown in Peat over Subsoil C (left panels) and Peat over Subsoil BC (right panels) in 2017 and 2018. The effect of fertilizer, tree species, and their interaction was tested within each soil group and year. Letters indicate statistically significant differences between means in fertilizer treatments (α≤0.1, n=6).

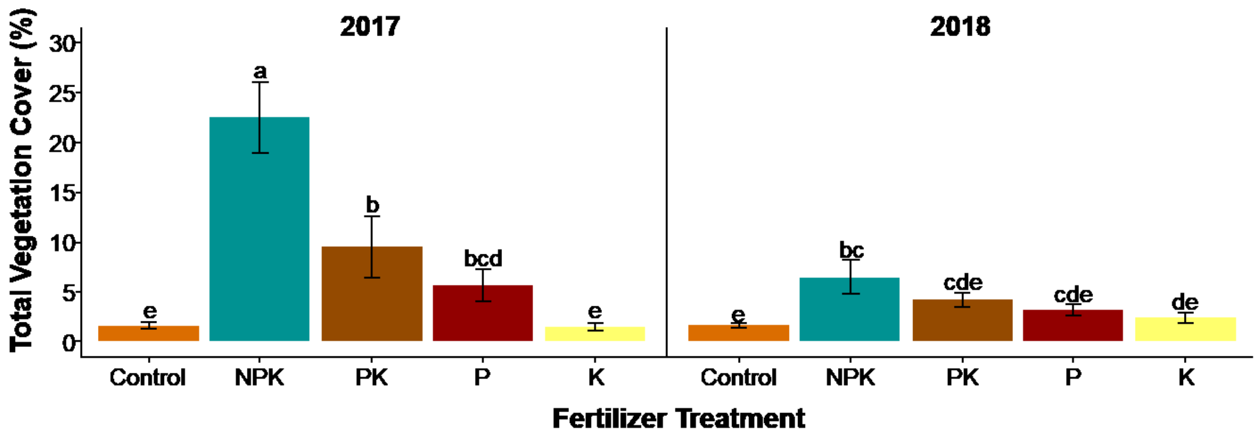

Figure 3-4: Total understorey vegetation cover (%) (±SE) for each fertilizer treatment in 2017 and 2018. Letters indicate statistically significant differences between vegetation cover means in fertilizer treatments across both years (α≤0.1, n=36).

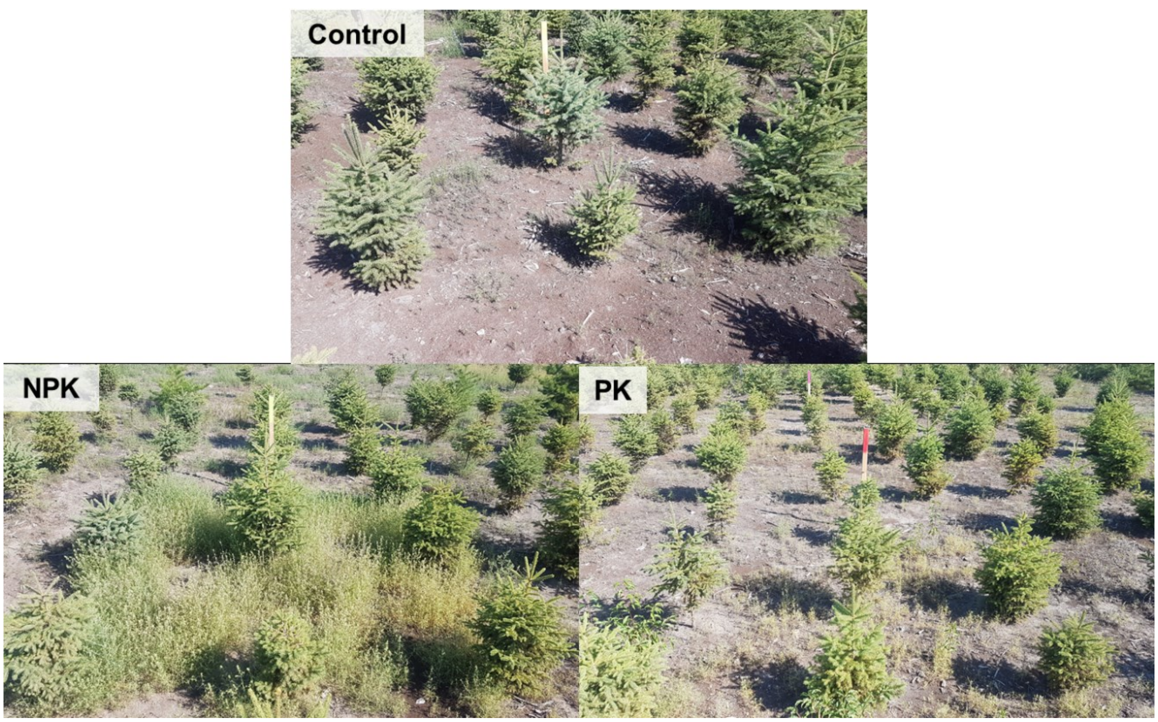

Figure 3-5: Photos show understorey vegetation response, specifically of *Salsola pestifer* A. Nels., in the Control, NPK, and PK fertilizer plots in 2017.

Chapter 4: Synthesis and Discussion

4.1 Research Summary

The overall objective of this thesis was to assess the effects of different reclamation soil materials, their placement designs, and a fertilizer amendment targeting individual soil nutrients on tree seedling development and soil edaphic conditions in upland forest reclamation of surface mines. In Chapter 2, the impact of 1) coversoil material type, 2) placement depths of these coversoil materials, and 3) subsoil material type on the establishment and growth of three boreal upland tree species over the first five years since planting was assessed. A follow-up study was discussed in Chapter 3, where a targeted fertilizer application of individual nutrients (i.e. NPK, PK, P, K, and a Control) was tested for its ability to supplement nutrient limitations in the soil materials and the targeted tree seedlings, while reducing the competitive response of colonizing vegetation that often renders fertilizer amendments ineffective.

In Chapter 2, coversoil material type and the amount placed at the soil surface were the strongest drivers of tree seedling growth over the first five growing seasons, and these results can be explained by the interaction between resource availability and seedling responses to the coversoils. The pioneer species in this study, trembling aspen and jack pine, exhibited a more pronounced response to the coversoil treatments compared to the late-successional white spruce species. These differences in species-specific responses may have been driven by the substrate conditions such as the availability of less mobile nutrients like phosphorus and differences in soil temperature and water holding capacity, which subsequently impacted resource availability (i.e. nutrients and water). Given their early successional life strategies, aspen and pine require an abundant supply of essential nutrients and water in a warm soil environment to accommodate their fast growth rates during establishment, which explains their slower growth on the peat coversoil that had lower levels of phosphorus and lower soil temperatures compared to the FFM. However, the impact of limited water availability on aspen and pine was apparent in the coarse-textured FFM coversoil during the dry growing conditions of 2015, while water content in the peat coversoil remained consistently higher and more available. The type and amount of organic matter dictated the differences in soil temperature and moisture conditions between the coversoils, where peat and its placement in thick layers (i.e. 30cm) created insulating conditions that lowered seasonal soil temperatures and delayed soil warming each spring; alternatively, the lower organic content in the coarse FFM resulted in low water availability, which limited seedling growth during dry years.

The underlying subsoil material also influenced growth, particularly later in establishment when roots of the faster growing species (i.e. aspen and pine) occupied the deeper subsoil layers. Aspen growth was greatest on soil covers containing the selectively salvaged layer of weathered Bm subsoil compared to the more deeply salvaged and less weathered subsoils BC and C; in this case, the higher availability of phosphorus in the Bm subsoil was correlated with the growth response in aspen. Differences in the silt fraction in the subsoils likely impacted aspen and pine growth by increasing the water holding capacity of these otherwise coarse textured sandy soils, whereas lower silt fraction in the BC subsoil resulted in a lower water content during the dry growing conditions of 2015 and a subsequent decrease in seedling growth that continued into the following growing season. Spruce regeneration responded minimally during this initial five-year study because this slow-growing species is adapted and tolerant to resource limitations given its late-successional status and ability to grow in competitive conditions under a canopy cover of pioneer species.

In Chapter 3, aspen had responded the strongest to targeted fertilization on peat coversoils placed over homogenous subsoil materials, particularly in the P treatment, while pine and spruce marginally responded to the NPK treatment; however, the responses were strongly dependent on the interaction between the physical and chemical properties of the reconstructed soil materials and the total capping depth of the soil cover. All species showed deficient levels of phosphorus in their foliar pools, while pine and spruce showed a deficiency in N through their foliar nitrogen concentrations and N:P ratios despite the fertilizer additions, suggesting the amount of nutrients added was not large enough to fully amend the nutrient limitations within the trees. Furthermore, these results indicated that the conifer species were more limited by nitrogen availability rather than phosphorus, unlike aspen trees that were more sensitive to phosphorus additions given the strong growth response observed in the P treatment.

Responses to targeted fertilization were greatest in the deeper soil cover (i.e. 1.5m of peat over subsoil C) compared to the shallower placement (i.e. 0.6m of peat over subsoil BC). Considering the hydrological overburden boundary was closer to the peat layer in the peat/BC soil cover, water content was higher in the lower part of the peat coversoil layer, and considering the insulative properties associated with this material and the heating capacity of water, this created cooler conditions in the root zone that likely slowed the uptake rate of nutrients each growing season. The alkaline pH and calcium concentrations may have further reduced the availability of phosphorus in the peat coversoil by increasing the sorption of phosphorus onto the soil particles and the formation of precipitates with calcium, which likely reduced the available phosphorus concentrations for tree use.

Seasonal conditions were significantly drier in the first growing season when the fertilizer was applied, which could explain the minimal growth in this year compared to the second growing season that was wetter. This suggests the amount of water applied during fertilizer application was likely not enough to infiltrate the nutrients into the root zone where it would be accessible by the trees. Competing vegetation dominated by the noxious species *Salsola pestifer* increased in the NPK treatment and did not respond to the P, K, and Control treatments, supporting the theory that targeting individual nutrients when broadcasting fertilizer, with the exception of nitrogen, can help reduce the response of competing vegetation. Considering the dry conditions when the fertilizer was applied, the drought tolerant species *S. pestifer* was able to take advantage of the fertilizer that resided at the peat surface, specifically in the plots where NPK and PK were applied in combination.

4.2 Management Implications and Further Research

The selection of a suitable coversoil for upland reclamation is a critical step because this material will govern the early establishment and growth of planted tree seedlings, whose roots will be isolated to this layer during the initial years after planting. If available for reclamation, salvaged upland FFM is the best option for coversoil reconstruction given the positive responses we observed in planted tree seedlings during early establishment, and this is a common finding from other studies as well (Macdonald et al., 2015b; Pinno et al., 2012a). Upland salvaged soil materials tend to have higher levels of available phosphorus to support the establishment and growth of planted seedlings (Howell et al., 2016, 2017; MacKenzie and Quideau, 2012), provide the inoculants for building microbial communities that are native to upland areas and important for initiating nutrient cycling processes (Beasse et al., 2015; McMillan et al., 2007), and supply a propagule bank that supports the development of a native upland understory community as planted trees reach canopy closure (Hahn and Quideau, 2013; Macdonald et al., 2015a; Mackenzie and Naeth, 2010). Our study showed that thin placements (i.e. 10cm) of FFM as a coversoil will produce the same results as a thick placement (i.e. 20cm), in both the planted tree seedlings and the understory community cover (Jones and Landhäusser, 2018); considering the low availability of this material, using less FFM while achieving the same results can improve the efficient use of this material and increase the potential area that it may cover.

The alternative and more abundant peat material demonstrated properties that can either support or limit the early establishment of planted tree seedlings in upland sites, and this is dependent on its placement thickness at the soil surface. In our study, the porous structure and the lack of mineral soil mixed into the peat was able to hold significantly more water during dry growing conditions compared to the sandier FFM, supporting the continuous growth of the planted tree seedlings even during dry periods. Peat can be a valuable material for retaining soil moisture during the early stages of forest recovery when vegetation cover is low and the bare soil surface is exposed to the drying effects of wind and solar heat, particularly in the context of a changing climate where years with low precipitation are becoming more common (Kljun et al., 2006; Krishnan et al., 2006). However, placing pure peat materials in thick layers (i.e. 30cm) at the surface can not be recommended considering the insulative properties of this material that can create cool soil conditions with an increasing proportion of organic matter (Turetsky et al., 2000; Zhao and Si, 2019), which delays soil warming each spring, slows the uptake rate of water and nutrients, and reduces growth in the planted tree seedlings as shown in this study and others (Greene et al., 2007; Lafleur et al., 2015; Wan et al., 1999).

Generally, when using peat as a coversoil, a mixture of the peat with mineral soil (peat-mineral-mix) is recommended for upland reclamation. This coversoil type can be created by salvaging part of the underlying mineral soil with the peat and placing these materials on site as a mixture (Moskal et al., 2001; Ojekanmi & Chang, 2014; Rowland et al., 2009). However, in this study, the mineral soil underlying the peat was not included because it had high levels of calcium carbonate creating high pH conditions that affect the growth of pH sensitive species like aspen and pine (Howat, 2000; Zhang et al., 2015, 2016). If the underlying mineral soil is not suitable for inclusion, it is important to consider other sources of mineral soil, such as upland subsoils, that can be incorporated into the peat to improve drainage and the textural consistency within the coversoil layer; by doing so, the insulative effects will be reduced, allowing the coversoil to warm faster and to remain warmer throughout the growing season, while still retaining its ability to store enough water for the establishing vegetation (Ojekanmi and Chang, 2014; Zhao and Si, 2019). Incorporating and layering peat with FFM may be an alternative option to a mineral mix, where the FFM would provide the essential nutrients for initial establishment, the microbial communities to initiate nutrient cycling processes, and native upland vegetation through its propagule bank, and the peat could store and supply the water needed to support the growing vegetation and provide nitrogen and sulfur through mineralization of its organic matter (MacKenzie and Quideau, 2012; Naeth et al., 2013).

If peat is the only material used in the coversoil layer, amendments may be required to ameliorate the limiting soil nutrient conditions, and the nutrient prescription used will depend on the targeted tree species that are planted on site. In this study, phosphorus and potassium in the peat materials were significantly lower than in the FFM, and they were perceived as being the nutrients most limiting to tree growth (Howell et al., 2016; 2017; MacKenzie and Quideau, 2012). However, responses to the fertilizer treatments varied by species where the deciduous aspen responded to the targeted P treatment while the conifers showed a sensitivity to nitrogen availability. When fertilizing mixed-species stands in upland reclaimed areas, it is important to design a nutrient prescription that targets an individual species because a single prescription may not benefit all mixed-wood species given their different life strategies and resources requirements (Chapin III et al., 1986; Kronzucker et al., 1997; Lavoie et al., 1992; Pinno et al., 2012a, 2012b). In this study, the best approach may be to target the fast-growing deciduous species that have extensive root systems capable of readily using the applied nutrients, which will increase the leaf litter output over a shorter period of time and improve the nutrient cycling processes and nitrogen availability for conifer development in later years (Attiwill and Adams, 1993; Cole, 1995; Foster and Bhatti, 2006). Furthermore, it is recommended that a single nutrient like phosphorus or potassium is targeted and applied when using a broadcasting application because this will reduce the competitive response of unwanted vegetation that is typically driven by the additions of nitrogen in combination with other essential nutrients (Pinno and Errington, 2015; Pokharel et al., 2017; Sutton, 1995; van den Driessche et al., 2005).

Prior to fertilization, it is important to consider the potential interactions between the added nutrients, soil conditions, and the trees targeted for fertilization. The peat in this study had very high levels of calcium and a slightly alkaline pH of 8 that may have reacted with the phosphorus that was added and reduced its availability (Bell and Black, 1970; Tunesi et al., 1999). Ideally, a preliminary laboratory study could have been used to assess the appropriate application rate of phosphorus fertilizer by accounting for the amount that the soil would adsorb before excess is made available for plant use. In this study, the high calcium availability and alkaline pH was likely a legacy from calcium carbonate found in the mineral soil underlying the peat at the salvage site. Peat was salvaged to the mineral contact boundary, and considering the wet environment of these lowland sites, calcium carbonate likely diffused from the mineral soil into the lower peat layers. Avoiding these lower peat layers during salvaging may be the best approach to prevent the development of soil chemical properties in the coversoil that reduce the availability of other nutrients (i.e. phosphorus) and impair root water uptake (Tang et al., 1993; Zhang et al., 2015, 2017; Zhang and Zwiazek, 2016). As for available nitrogen in the peat, a preliminary assessment could have also been applied to the conifer species to determine the appropriate application ratio of nitrogen to phosphorus, which could have created the optimal balance of these two nutrients for the benefit of pine and spruce (Gusewell, 2004; Tessier and Raynal, 2003).

The type of subsoil material and the depth and thickness of its placement can greatly influence the chemical and physical conditions in either coversoil material, as observed in this study. When working with coarse-textured materials commonly salvaged from upland Brunisols, it is important to consider the silt content and its role in improving the water holding ability of these coarse materials, even when the differences in the silt fraction are small (i.e. 1-3%) (Zettl et al., 2011). Creating textural heterogeneity using layers of subsoil materials that form hydrological boundaries can improve the water holding capacity of coarse soils and reduce the risk of drought stress during dry growing seasons (Huang et al., 2013; Krishnan et al., 2006). In the targeted fertilizer study, the distance between the peat layer and the subsoil-overburden boundary highlighted the importance of subsoil placement thickness and how it influences physical properties at the soil surface. When this boundary, which was semi-permeable, is closer to the pure peat layer, infiltration of water will slow as it approaches this boundary and create wetter conditions (Huang et al., 2013; Jackson et al., 2011); while this would be beneficial for the coarser FFM or thin layers of peat coversoil, this created cooler conditions in the thick peat layer on the shallow soil cap (i.e. 60cm) that may have limited the ability of roots to absorb the applied nutrients and reduced the growth responses of trees to the fertilizer prescription (Wan et al., 1999). Therefore, greater distance between thick layers of peat at the surface and the underlying hydrological boundaries can improve drainage in the peat coversoil and prevent the development of soil temperature limitations. Finally, placing a weathered and selectively salvaged Bm subsoil layer directly under the coversoil could provide the phosphorus that is typically limiting in peat materials, and placing either thinner layers of peat or peat-mineral mixes at the surface could improve the below-ground growth of seedlings and reduce the time and distance required for their roots to reach this subsoil layer (Faget et al., 2013; Strong and La Roi, 1983a; Tryon and Chapin III, 1983).

Future research should focus on the concept of layering or mixing FFM and peat materials in upland reclaimed sites, and assess the impact of the water holding ability provided by the peat layer in conjunction with the nutritional, microbial, and propagule benefits associated with the FFM on tree growth, particularly in comparison to the pure FFM coversoils we observed in our study. Incorporating layers of different texture during subsoil placement on future sites could solidify our speculation about the major role that small amounts of silt (i.e. ~3%) can have in the water holding ability of the coarse soils used in upland reclamation. Determining the appropriate application rates of the nutrients we tested on the peat materials, while considering the calcium and pH levels in the case of phosphorus, could provide an approximate application rate recommended for future sites with these conditions and reduce the risk of an ineffective nutrient treatment. Considering the conifer species responded minimally to targeted fertilization of phosphorus and potassium, future work could determine the appropriate nutrient prescription that may be used for targeting limitations for pine and spruce, which could be nitrogen given the results from this study or other micro-nutrients that we did not research.

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Appendix A: Figures

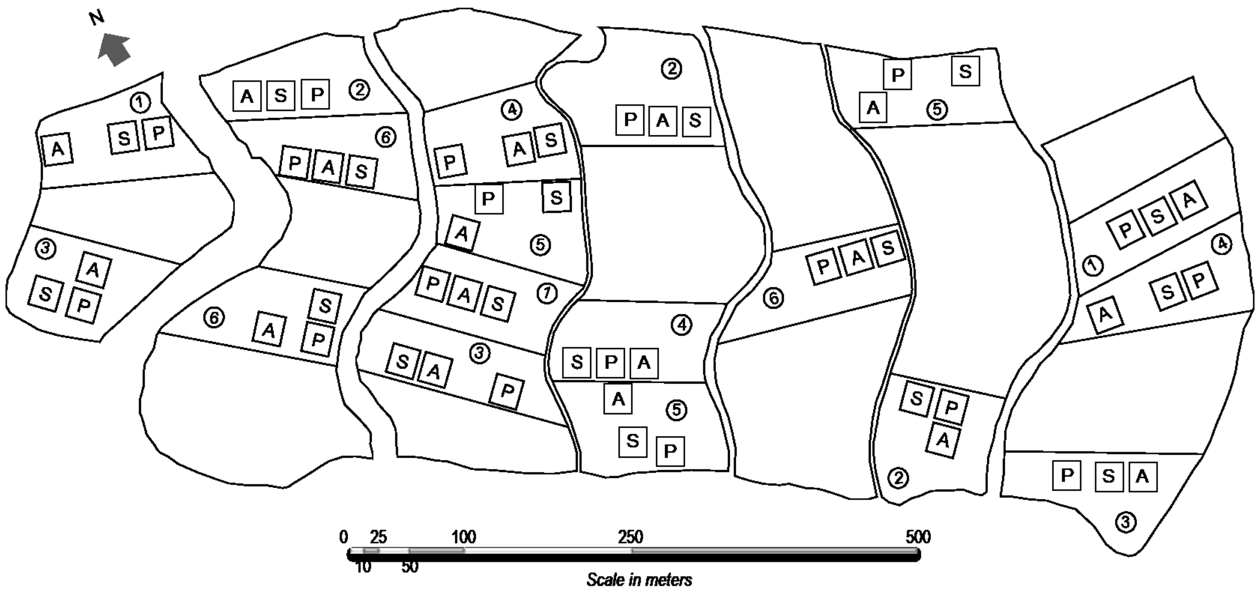

Figure A-1: Map of the Aurora Soil Capping Study (ASCS). The soil layering treatment is designated by a circle in each cell, and tree plots are designated as squares with their planting treatment identified within. ‘A’ refers to trembling aspen, ‘P’ refers to jack pine, and ‘S’ refers to white spruce.

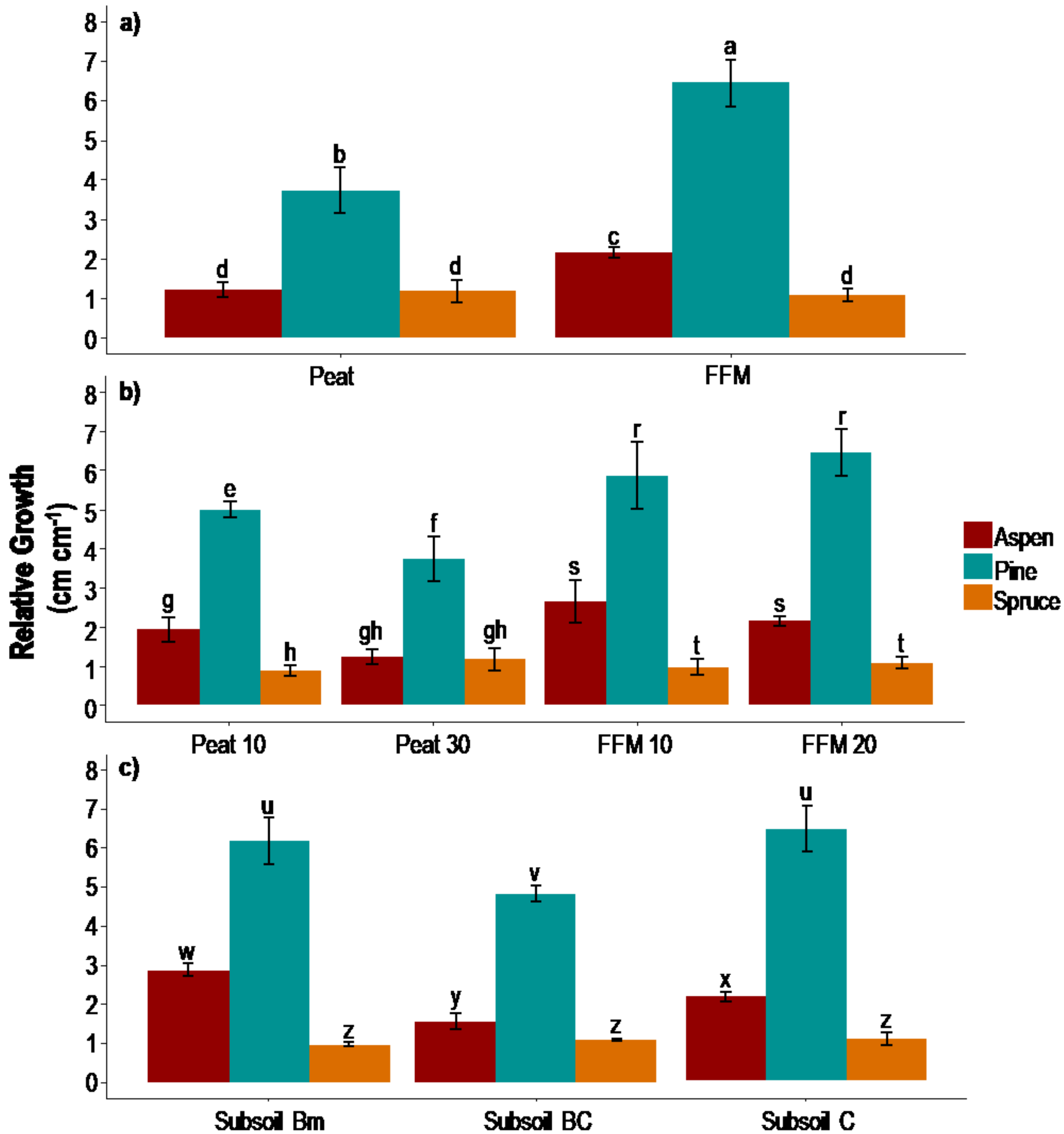

Figure A-2: Mean (±SE) tree growth from 2012-2016 relative to initial 2012 height for trembling aspen, jack pine, and white spruce in different: a) coversoil material types, b) depths of Peat and FFM, and c) subsoil material types. Letters indicate significant differences between tree species growth means and soil treatment ($\alpha \leq 0.1$, n=3). Relative growth in b) was analyzed separately within Peat and FFM coversoils.

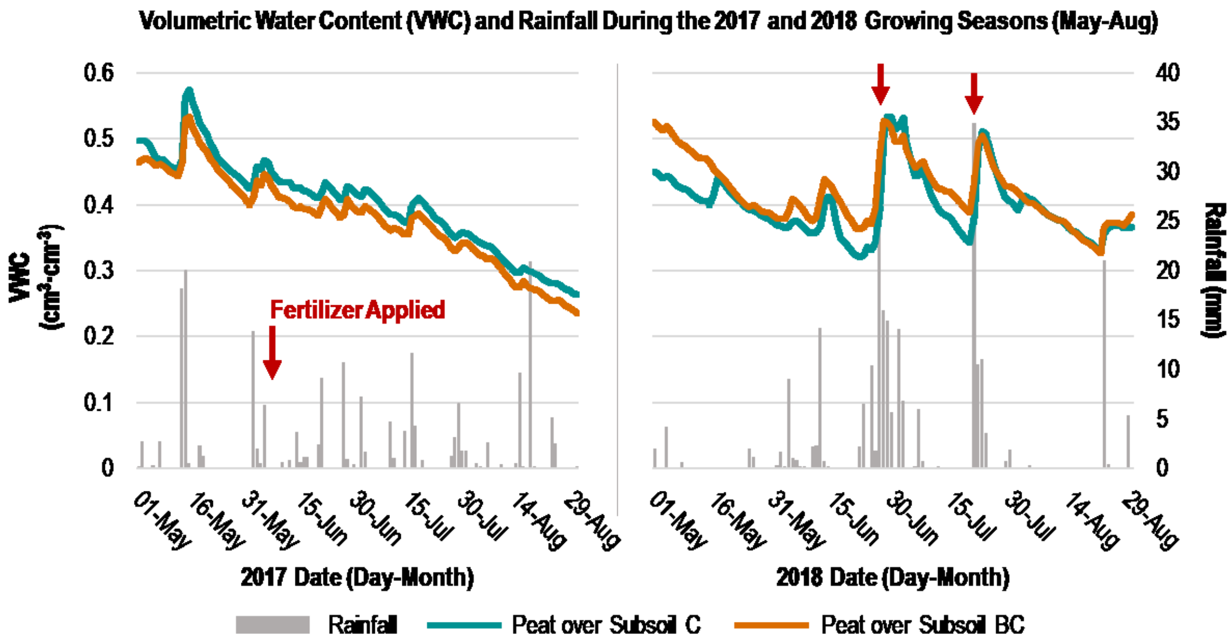

Figure A-3: Daily average volumetric water content (VWC) measured 15cm below the soil surface (i.e. within the Peat coversoil layer) for the 2017 and 2018 growing seasons (May 1 to August 31) in the Peat/Subsoil C and Peat/BC soil covers. Bars shown in the background represent total daily rainfall. Red arrow in the 2017 graph shows point when fertilizer was applied, and arrows in the 2018 graph indicate important precipitation events that maintained water content levels above the wilting point of plants (25%; Ojekanmi & Chang, 2014) in the Peat material.

Appendix B: Tables

Table B1: Mean (±SD) initial seedling characteristics at out planting in 2012 (n=20).

Species	Height (cm)	Shoot mass (g)	Root mass (g)	RSR	Plug height (cm)	Plug diameter (cm)	Plug volume (ml)
Aspen	30 (8.6)	0.7 (0.4)	2.5 (1.2)	3.4	15	6	340
Pine	18.2 (2.8)	2.2 (0.7)	1.3 (0.5)	0.6	12	4	125
Spruce	29 (5.5)	4.5 (1.6)	2.9 (1.4)	0.7	15	6	340

RSR = Root shoot ratio

Table B-2: Average height and root collar diameter (RCD) (±SE) of trembling aspen, jack pine, and white spruce grown in Peat over Subsoil C and Peat over Subsoil BC from 2016-2018 (n=6). Five fertilizer treatments (i.e. Control, NPK, PK, P, K) were applied after the 2016 measurement.

Species	Growth Parameter	Year	Peat/Subsoil C					Peat/Subsoil BC				
			Control	NPK	PK	P	K	Control	NPK	PK	P	K
Trembling Aspen	Height (cm)	2016	94.8 (5.6)	88.1 (9.8)	97.1 (11.7)	98.2 (12.2)	90.1 (8.9)	90.1 (10.7)	105.1 (6.5)	92.3 (9.3)	94.0 (9.1)	109.2 (5.4)
		2017	114.2 (7.5)	106.8 (10.8)	117.7 (11.8)	124.7 (13.7)	113.9 (12.2)	106.0 (10.6)	119.4 (5.0)	109.4 (10.7)	108.2 (13.7)	125.0 (4.4)
		2018	125.7 (11.8)	125.3 (14.1)	137.7 (13.8)	151.8 (18.8)	123.8 (12.1)	113.0 (11.7)	133.8 (6.9)	122.4 (11.9)	119.9 (15.8)	136.1 (6.8)
	RCD (mm)	2016	14.5 (1.3)	13.4 (1.3)	16.0 (1.7)	14.9 (1.2)	13.7 (0.9)	14.1 (1.1)	14.5 (0.7)	13.5 (0.9)	13.6 (1.3)	15.6 (0.6)
		2017	16.8 (1.4)	16.3 (1.4)	17.8 (1.8)	17.9 (1.5)	17.2 (1.3)	16.4 (1.4)	17.8 (0.5)	16.5 (1.2)	16.7 (1.8)	18.3 (0.7)
		2018	19.1 (1.7)	20.1 (1.7)	20.8 (1.9)	21.7 (1.5)	20.8 (1.7)	18.6 (1.8)	20.7 (0.9)	19.5 (1.4)	19.5 (1.9)	20.9 (0.8)
Jack Pine	Height (cm)	2016	116.7 (12.0)	113.4 (9.8)	117.6 (7.7)	113.3 (10.1)	114.3 (8.4)	83.3 (13.1)	84.9 (15.0)	90.3 (10.8)	91.6 (9.4)	84.3 (11.9)
		2017	159.9 (15.3)	166.8 (11.9)	164.0 (9.3)	158.7 (14.8)	161.9 (9.6)	118.1 (19.5)	111.1 (16.8)	124.0 (11.9)	127.8 (8.7)	114.8 (11.0)
		2018	196.7 (15.3)	208.1 (11.5)	201.5 (11.7)	196.5 (16.9)	202.0 (10.3)	151.0 (21.8)	146.3 (18.3)	163.8 (13.3)	169.9 (9.1)	149.0 (13.5)
	RCD (mm)	2016	29.0 (2.3)	29.9 (1.3)	29.9 (1.1)	27.6 (2.5)	28.4 (2.0)	22.9 (2.7)	21.8 (3.1)	24.4 (2.1)	24.3 (1.5)	22.6 (1.9)
		2017	33.8 (2.5)	36.4 (1.7)	34.8 (1.5)	34.4 (2.2)	34.8 (1.9)	27.6 (3.2)	26.5 (3.5)	29.3 (2.0)	29.7 (1.5)	27.0 (1.4)
		2018	40.1 (2.4)	43.7 (1.5)	42.0 (1.6)	39.6 (3.0)	40.5 (2.3)	34.3 (3.5)	34.0 (3.8)	37.7 (2.2)	37.8 (1.4)	34.8 (1.6)
White Spruce	Height (cm)	2016	71.1 (5.2)	71.2 (3.9)	70.0 (4.7)	70.8 (5.2)	74.2 (7.0)	70.8 (4.4)	71.9 (5.0)	70.0 (3.8)	79.2 (3.5)	74.2 (4.1)
		2017	85.7 (6.1)	87.4 (4.4)	84.3 (6.4)	83.1 (5.6)	90.4 (7.6)	85.4 (3.4)	85.6 (7.2)	84.8 (4.3)	99.0 (4.1)	91.5 (4.8)
		2018	93.9 (6.8)	98.1 (5.3)	92.7 (7.6)	91.2 (5.9)	99.9 (8.4)	94.4 (3.6)	101.8 (7.5)	95.9 (4.3)	112.0 (3.6)	104.3 (5.5)
	RCD (mm)	2016	21.6 (0.7)	22.5 (0.8)	21.4 (1.2)	21.6 (1.3)	22.6 (1.0)	21.7 (1.0)	22.6 (1.6)	21.5 (0.9)	23.0 (0.9)	22.1 (1.0)
		2017	24.2 (0.6)	24.9 (0.8)	24.4 (1.4)	24.3 (1.5)	26.0 (0.9)	25.9 (1.0)	26.3 (1.7)	25.1 (1.5)	27.4 (1.2)	26.9 (1.1)
		2018	27.3 (0.7)	29.3 (1.3)	27.6 (1.6)	27.4 (1.6)	29.0 (1.4)	30.4 (1.0)	31.4 (1.8)	29.6 (1.8)	32.8 (1.7)	31.2 (1.6)

Table B-3: Foliar nutrient concentrations (±SE) of trembling aspen, jack pine, and white spruce grown in five fertilizer treatments in the Peat over Subsoil C and Peat over Subsoil BC soil covers during the 2017 and 2018 growing seasons (n=6).

Soil Cover	Tree Species	Foliar Nutrient	2017 Control	2017 NPK	2017 PK	2017 P	2017 K	2018 Control	2018 NPK	2018 PK	2018 P	2018 K
Peat over Subsoil C	Trembling Aspen	N	2.41 (0.10)	2.52 (0.12)	2.41 (0.08)	2.33 (0.07)	2.67 (0.10)	2.05 (0.04)	2.05 (0.08)	2.06 (0.09)	1.98 (0.06)	2.18 (0.07)
		P	0.30 (0.03)	0.31 (0.03)	0.28 (0.02)	0.28 (0.03)	0.31 (0.02)	0.07 (0.00)	0.08 (0.00)	0.08 (0.00)	0.09 (0.01)	0.07 (0.00)
		K	1.12 (0.05)	1.11 (0.03)	1.12 (0.06)	1.17 (0.06)	1.27 (0.05)	0.84 (0.03)	0.85 (0.03)	0.87 (0.02)	0.90 (0.02)	0.83 (0.02)
		S	0.06 (0.00)	0.07 (0.00)	0.07 (0.00)	0.06 (0.00)	0.06 (0.00)	0.26 (0.01)	0.25 (0.01)	0.25 (0.01)	0.25 (0.00)	0.27 (0.01)
		Ca	1.30 (0.07)	1.38 (0.08)	1.33 (0.12)	1.32 (0.05)	1.31 (0.10)	0.98 (0.05)	1.09 (0.06)	1.07 (0.04)	1.06 (0.03)	1.06 (0.05)
		Mg	0.21 (0.01)	0.19 (0.01)	0.17 (0.01)	0.21 (0.02)	0.16 (0.01)	0.18 (0.00)	0.17 (0.01)	0.17 (0.01)	0.18 (0.01)	0.18 (0.01)
	Jack Pine	N	1.35 (0.11)	1.29 (0.09)	1.18 (0.13)	1.31 (0.09)	1.32 (0.11)	1.03 (0.14)	0.97 (0.10)	1.03 (0.13)	1.06 (0.13)	1.06 (0.14)
		P	0.10 (0.00)	0.12 (0.01)	0.11 (0.00)	0.11 (0.00)	0.12 (0.01)	0.09 (0.00)	0.11 (0.01)	0.10 (0.01)	0.11 (0.01)	0.09 (0.01)
		K	0.51 (0.01)	0.54 (0.03)	0.56 (0.03)	0.52 (0.03)	0.60 (0.05)	0.61 (0.05)	0.60 (0.03)	0.58 (0.05)	0.59 (0.03)	0.64 (0.04)
		S	0.07 (0.00)	0.08 (0.00)	0.07 (0.01)	0.07 (0.00)	0.08 (0.01)	0.11 (0.01)	0.11 (0.01)	0.11 (0.01)	0.11 (0.01)	0.12 (0.01)
		Ca	0.21 (0.01)	0.20 (0.01)	0.19 (0.01)	0.20 (0.01)	0.19 (0.01)	0.30 (0.06)	0.31 (0.07)	0.31 (0.06)	0.29 (0.07)	0.27 (0.04)
		Mg	0.10 (0.00)	0.11 (0.00)	0.10 (0.00)	0.10 (0.00)	0.10 (0.00)	0.10 (0.00)	0.10 (0.00)	0.10 (0.01)	0.09 (0.01)	0.10 (0.01)
	White Spruce	N	0.92 (0.01)	1.17 (0.11)	0.84 (0.09)	0.93 (0.09)	0.96 (0.06)	0.81 (0.11)	0.77 (0.10)	0.75 (0.08)	0.80 (0.10)	0.75 (0.08)
		P	0.08 (0.00)	0.09 (0.00)	0.08 (0.01)	0.08 (0.00)	0.09 (0.00)	0.08 (0.01)	0.09 (0.01)	0.09 (0.01)	0.08 (0.01)	0.08 (0.01)
		K	0.41 (0.02)	0.42 (0.02)	0.40 (0.03)	0.39 (0.03)	0.41 (0.02)	0.63 (0.06)	0.60 (0.06)	0.63 (0.07)	0.60 (0.07)	0.63 (0.08)
		S	0.05 (0.00)	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)
		Ca	0.58 (0.04)	0.61 (0.04)	0.51 (0.02)	0.54 (0.04)	0.63 (0.03)	0.36 (0.05)	0.41 (0.03)	0.37 (0.02)	0.41 (0.03)	0.40 (0.03)
		Mg	0.08 (0.00)	0.09 (0.00)	0.08 (0.00)	0.07 (0.00)	0.08 (0.00)	0.09 (0.00)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)
Peat over Subsoil BC	Trembling Aspen	N	2.19 (0.19)	2.52 (0.09)	2.18 (0.14)	2.45 (0.09)	2.32 (0.06)	2.16 (0.11)	1.97 (0.08)	1.96 (0.08)	1.95 (0.08)	2.18 (0.04)
		P	0.36 (0.01)	0.35 (0.03)	0.34 (0.02)	0.36 (0.02)	0.34 (0.04)	0.06 (0.00)	0.07 (0.00)	0.07 (0.00)	0.07 (0.00)	0.06 (0.00)
		K	0.96 (0.09)	0.98 (0.06)	1.16 (0.05)	1.07 (0.09)	1.11 (0.05)	0.75 (0.01)	0.87 (0.05)	0.90 (0.04)	0.83 (0.04)	0.78 (0.02)
		S	0.06 (0.00)	0.07 (0.01)	0.06 (0.00)	0.06 (0.01)	0.06 (0.00)	0.28 (0.01)	0.28 (0.02)	0.28 (0.01)	0.28 (0.02)	0.28 (0.03)
		Ca	1.30 (0.08)	1.35 (0.11)	1.30 (0.11)	1.36 (0.13)	1.23 (0.08)	0.94 (0.04)	1.05 (0.05)	1.11 (0.08)	1.06 (0.05)	0.95 (0.06)
		Mg	0.23 (0.02)	0.22 (0.02)	0.20 (0.01)	0.23 (0.01)	0.22 (0.01)	0.20 (0.01)	0.20 (0.01)	0.19 (0.01)	0.20 (0.01)	0.20 (0.00)
	Jack Pine	N	1.41 (0.20)	1.53 (0.15)	1.36 (0.19)	1.51 (0.13)	1.35 (0.19)	1.30 (0.03)	1.31 (0.05)	1.22 (0.03)	1.21 (0.05)	1.33 (0.03)
		P	0.12 (0.01)	0.12 (0.01)	0.12 (0.00)	0.12 (0.01)	0.12 (0.01)	0.08 (0.01)	0.11 (0.01)	0.10 (0.01)	0.11 (0.01)	0.09 (0.01)
		K	0.42 (0.04)	0.46 (0.06)	0.49 (0.03)	0.46 (0.04)	0.47 (0.04)	0.52 (0.03)	0.57 (0.02)	0.62 (0.02)	0.54 (0.02)	0.64 (0.04)
		S	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.14 (0.00)	0.15 (0.01)	0.14 (0.00)	0.14 (0.01)	0.15 (0.01)
		Ca	0.32 (0.06)	0.33 (0.05)	0.31 (0.03)	0.31 (0.05)	0.32 (0.03)	0.26 (0.02)	0.25 (0.02)	0.23 (0.01)	0.23 (0.01)	0.24 (0.02)
		Mg	0.11 (0.00)	0.11 (0.01)	0.11 (0.00)	0.11 (0.00)	0.11 (0.01)	0.10 (0.00)	0.10 (0.00)	0.09 (0.00)	0.10 (0.00)	0.10 (0.00)
	White Spruce	N	1.15 (0.09)	1.18 (0.17)	1.10 (0.20)	1.06 (0.19)	1.09 (0.16)	0.74 (0.02)	0.79 (0.01)	0.73 (0.02)	0.77 (0.02)	0.79 (0.02)
		P	0.09 (0.01)	0.08 (0.00)	0.08 (0.00)	0.08 (0.00)	0.09 (0.01)	0.07 (0.00)	0.08 (0.00)	0.07 (0.01)	0.08 (0.00)	0.06 (0.00)
		K	0.33 (0.03)	0.29 (0.01)	0.31 (0.03)	0.26 (0.02)	0.34 (0.03)	0.63 (0.02)	0.62 (0.03)	0.65 (0.02)	0.61 (0.04)	0.68 (0.03)
		S	0.05 (0.00)	0.06 (0.00)	0.05 (0.00)	0.05 (0.00)	0.05 (0.00)	0.07 (0.00)	0.07 (0.00)	0.06 (0.01)	0.07 (0.00)	0.07 (0.00)
		Ca	0.62 (0.05)	0.68 (0.03)	0.61 (0.03)	0.58 (0.05)	0.62 (0.04)	0.41 (0.02)	0.45 (0.03)	0.44 (0.02)	0.47 (0.05)	0.45 (0.04)
		Mg	0.08 (0.00)	0.08 (0.00)	0.08 (0.01)	0.07 (0.00)	0.08 (0.01)	0.07 (0.00)	0.07 (0.00)	0.07 (0.00)	0.07 (0.00)	0.07 (0.00)

Table B-4: Soil temperature and volumetric water content (VWC) (±SE) measured at four different depths below the soil surface in Peat over Subsoil C and Peat over Subsoil BC. Letters indicate statistically significant differences between soil cover means within each year ($\alpha \leq 0.1$; n=3).

Variable	Depth	2017		2018	
		Peat/C	Peat/BC	Peat/C	Peat/BC
Soil Temperature (°C)	5 cm	16.2 (0.2)	15.5 (0.4)	16.2 (0.7)	16.0 (0.4)
	15 cm	14.9[a] (0.1)	13.7[b] (0.2)	15.1 (0.5)	14.3 (0.2)
	25 cm	12.5[a] (0.3)	10.2[b] (0.5)	12.8 (0.8)	10.9 (0.7)
	35 cm	11.8[a] (0.5)	8.4[b] (0.4)	12.0[x] (1.1)	9.3[y] (0.4)
Soil VWC ($cm^3 \cdot cm^{-3}$)	5 cm	0.28 (0.04)	0.25 (0.07)	0.28 (0.03)	0.31 (0.07)
	15 cm	0.40 (0.05)	0.38 (0.07)	0.40 (0.04)	0.42 (0.07)
	25 cm	0.37 (0.08)	0.42 (0.08)	0.36 (0.07)	0.43 (0.08)
	35 cm	0.08 (0.007)	0.10 (0.009)	0.09[y] (0.007)	0.12[x] (0.01)

Table B-5: Plant available nutrients in undisturbed Brunisolic soils sampled from three natural sites near the ASCS in 2011 (n=3). The type of extraction method used to assess nutrient availability is positioned above the associated nutrient columns.

Soil Horizon	Average Thickness (cm)	Kelowna Method ($mg \cdot kg^{-1}$)			KCl Extract ($mg \cdot kg^{-1}$)	Saturated Paste ($mg \cdot kg^{-1}$)			
		NO_3	P	K	NH_4	K	SO_4	Ca	Mg
LFH	3	< 10	40	387	10	-	-	-	-
Bm	24	< 2	32	< 20	< 0.3	< 1	0.8	1.4	0.2
BC	39	-	-	-	-	< 1	0.5	0.2	0.1
C	17	-	-	-	-	< 1	0.6	0.4	0.1