The Role of Microtopographic Variation in Forest Reclamation

By

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Abstract

Surface mining is an anthropogenic disturbance which significantly alters natural ecosystems, involving the removal of vegetation, top and subsoils, and several metres of overburden material before accessing valuable resources. Forest reclamation efforts following surface mining face several challenges due to the severity of disturbances following resource extraction. This process begins with reforming landscape features using overburden materials which struggle to support the growth of forest vegetation. Salvaged soils are a suitable growth medium for planted tree seedlings and colonizing vegetation, however, current coversoil application practices fail to capture surface level spatial heterogeneity characteristic for natural forests. This variability contributes to altered soil edaphic conditions, providing a range of microsites suitable for the growth and establishment of trees and vegetation.

This study assessed how the creation of spatial heterogeneity on reclamation sites by mechanically manipulating coversoil types and microtopography (0 – 1 m scale) impacts the growth and establishment of planted *Populus tremuloides* (trembling aspen), *Pinus banksiana* (Jack pine) and *Picea glauca* (white spruce) seedlings and the natural colonization of woody species. At a finer scale, the growth responses of planted seedlings to specific microsite positions were also investigated. At an operational scale, two constructed microtopographical treatments (ridged and hilled) were compared to a levelled treatment which represents widespread operational practices. Two different coversoil materials (salvaged upland forest floor material (FFM) and lowland peat mineral mix (PMM)) were used.

The results from this study indicate that planted seedlings grew larger in height and root collar diameter in the treatment with the greatest microtopographic variation (hilled), particularly when applied on a south-facing site with greater exposure; however, the magnitude of the response differed among planted species. The natural colonization of woody species also increased with microtopographic variation, where the sheltered toe position in the hilled treatment and the PMM material type were preferred establishment sites. At the microsite scale, planted seedling growth differed more among planting positions on FFM (coarser) hills, while differences were small among microsites on hills made of PMM coversoil. Most of the observed responses appear to be driven by the availability of water rather than variations in temperature and nutrient conditions. As a result, the use of increased surface soil variation (via different coversoil materials and microtopography) will likely be more effective on reclamation sites with greater exposure to conditions such as drought and can significantly benefit forest restoration efforts on these exposed sites.

Preface

This study was initiated by Andrew Shaman in May of 2015 and overtaken by Trevor de Zeeuw in May of 2016. Data was collected by Andrew in 2015, and by Trevor in 2016 and 2017, and summarized, analyzed and interpreted by Trevor. The following thesis is the culmination of these efforts. No part of this thesis or the data herein has been published as of November 2019.

The land reclamation study presented in this thesis is part of a multi-study project initiated by Dr. Simon Landhäusser of the University of Alberta, Rob Vassov of Canadian Natural Resources, Canada's Oilsands Innovation Alliance, and the Natural Sciences and Engineering Research Council. Katherine Melnik has completed and published research regarding the understory vegetation responses to microtopographic treatments on this site, and an aggregate of Kate and Trevor's research will be continued by Sophie LeBlanc.

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Chapter 1: Disturbance and Microsite Heterogeneity

1.1 Industrial disturbance, the boreal forest and forest reclamation

The boreal forest is a large circumpolar biome that encompasses the northern latitudes of the northern hemisphere (Brandt et al. 2013). Within Canada, the boreal forest covers 270 million ha (Brandt et al. 2013) and contains valuable renewable and non-renewable resources such as water, timber and non-timber forest products, wildlife, and oil and gas reserves (Bogdanski 2008). The boreal forest biome consists dominantly of wooded land containing tree species well adapted to cold climates such as *Populus, Betula, Pinus, Picea, Abies* and *Larix* (Brandt 2009). The boreal forest is the dominant natural region in Alberta, covering approximately 58% (384,000 km^2) of the province (Natural Regions Committee 2006). Topography in this region is described as level to gently undulating, with small changes to elevation and relief initiating significant differences in soil moisture and the development of clearly defined upland and wetland vegetation communities (Natural Regions Committee 2006). Upland forest soils are dominantly Luvisols and Brunisols forming under jack pine (*Pinus banksiana* Lamb.) stands on xeric sites, or mixed canopies of trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss) on mesic sites, while Organic and Gleysol soils form in lowland areas such as wetlands beneath black spruce (*Picea mariana* (Miller) B.S.P.) and tamarack (*Larix laricina* (Du Roi) K. Koch) canopies (Natural Regions Committee 2006). Climatic conditions within Alberta's boreal forest are characterized as having long cold winters and short warm summers, where the mean annual temperature is +0.5 °C and mean annual precipitation is 460mm (Natural Regions Committee 2006).

Due to the expansive area covered by the boreal forest and its abundant resources, various forms of natural and anthropogenic disturbances are common throughout its range. Natural disturbances such as forest fires, insect and disease outbreaks are part of a healthy forest life cycle and promote natural regeneration of trees and vegetation in various species compositions (La Roi and Ostafichuk 1982). Natural disturbance events that initiate secondary regeneration of forested sites are relatively frequent throughout the boreal, as conifer stands are considered old growth at 180 years old (Bonar et al. 2003). The severity of these natural disturbances will influence the capability of forest systems to re-establish climax vegetation communities following a disturbance event (Holling 1973, Johnstone et al. 2016). Disturbances within the boreal forest are frequent, and occur at both large (multiple hectares) and small (square meters) scales (Rydgren et al. 2004). As such, species native to local disturbance regimes in forest systems have developed resiliency to commonly occurring natural disturbances (Franklin et al. 2000). Anthropogenic disturbances caused by natural resource extraction are common throughout the Canadian boreal forest as an estimated 24 million ha have been affected by the extraction of timber, mineral and energy resources, agriculture, and other land uses since 2010 (Pasher et al. 2013). The severity of anthropogenic disturbances can be outside of the range of natural disturbance regimes due to the extensive processes involved in resource extraction, short disturbance intervals, and high densities of disturbed areas (Pickell et al. 2013). As such, anthropogenically disturbed areas of the boreal forest often require intensive restoration efforts, which include the reconstruction of landscape topography and soil conditions, to re-establish pre-disturbance forest conditions (Burton and Macdonald 2011).

Increasing demand for oil and gas resources has led to greater development of mineral resource extraction north of Fort McMurray, Alberta. This area is termed the Athabasca Oil Sands Region (AOSR) and is rich in mineral resources and surface mines used for the ex-situ extraction of bitumen. Currently, 89 500 ha of surface minable area have been disturbed in the AOSR (Government of Alberta 2018). Extracting bitumen through surface mining is an intensive process which involves the removal of all materials overlying the valuable resource, including timber and vegetation, forest soils, unconsolidated rock, and lean oil sands which have low oil concentrations (<10%) (Macdonald et al. 2012). The high severity of disturbance associated with bitumen extraction and other surface mining operations requires the development of both reclamation policy and a wide variety of reclamation practises to protect and restore the natural environment post-anthropogenic disturbance.

Under the Alberta *Environmental Protection and Enhancement Act*, all lands disturbed by industrial activities (excluding forestry and agriculture) must be returned to a natural state, equal to pre-disturbance conditions (Government of Alberta 2000, 2009, Powter et al. 2012). Similar regional regulatory frameworks have been introduced throughout North America to assist in best management practices following industrial development. However, these guidelines may inadvertently oversimplify reclamation processes. For example, the Surface Mining Control Act and the Forestry Reclamation Approach in the United States assisted with restoration guidelines following surface mining, but limited forest reclamation practices by promoting the grading of soils and the establishment of early successional grass species to limit soil erosion (Angel et al. 2009, Skousen and Zipper 2014). Common reclamation practices emphasize quick establishment of early successional species on the site, aiding the development of understory plant communities and functioning soil-plant nutrient cycles (Holl 2002, Rowland et al. 2009). However, an understanding of ecosystem processes is needed to develop self-sustaining reclaimed lands (Straker and Donald 2008), requiring the application of ecological and successional principles and investing research into reclamation methods to best achieve site specific goals.

1.2 Surface Mine Reclamation

Development of surface mines in the sedimentary basin of Alberta began to intensify in 2000, following the early success of operational scale trials in 1967 (Brandt et al. 2013). During the oil sand extraction process, 15-50m of material must be removed to reach bitumen rich sedimentary layers (Rowland et al. 2009). Removed materials include trees and vegetation, forest and peatland soils, and unconsolidated overburden material and rock. Merchantable forest stands are harvested, and underlying surface soils are either stockpiled or placed on an existing reclamation site (Bradshaw 2000). Overburden can be used to form the foundation of reclamation sites by using the material to cap partially solidified mine tailings, fill in excavated areas, or to create large landscape features, often generating greater landscape topographic heterogeneity than was present pre-disturbance (Rowland et al. 2009, Macdonald et al. 2015a). Overburden material can have characteristics which are detrimental to vegetation establishment, such as restricted water holding capacity, increased bulk density and salinity, and poor nutrient and pH conditions (Sloan and Jacobs 2013, Onwuchekwa et al. 2014). These poor conditions often require the use of topsoil caps or coversoils to facilitate plant growth (Flath 2009, Onwuchekwa et al. 2014).

Salvaged surface soils from undisturbed sites are often used as topsoil replacements (coversoils) in oil sands reclamation. Coversoils are classified based on the characteristics of the environment from which they were sourced and can generally be classified as forest floor material (FFM) from upland forests, and peat mineral mix (PMM) from lowland forests. Forest floor material is composed of the litter, fibre and humic organic layers, and the mineral A and B horizons to a depth of approximately 30 cm. The proportion of mineral soil and peat components in salvaged PMM can vary greatly depending on the salvage depth during removal but is generally characterized by having a high organic matter content. Peat mineral mix coversoil is available in greater volumes than FFM due to the accumulation of several meters of peat and organic material above mineral soils in wetlands and lowland forests (Macdonald et al. 2012). Salvaged coversoils are applied to a site following the contouring of underlying materials, typically to a depth of 20-50 cm to accommodate the larger root structures of trees and shrubs (Macdonald et al. 2012).

Establishing and maintaining a diverse vegetation community is a continuing challenge on boreal forest reclamation sites (Macdonald et al. 2015a) which can be enhanced by the establishment of a closed canopy composed of trees and shrubs native to the area (Parrotta et al. 1997, Macdonald et al. 2015b). Mixed species forest canopies contribute to heterogeneous edaphic conditions by altering understory resource availability and microclimatic conditions, which are important to the establishment of a diverse vegetation community (Macdonald and Fenniak 2007). Natural tree regeneration from seed is one method to re-establish a forest canopy, however this method can have varying levels of success due to seed availability and viability, dispersal mechanisms and proximity to the site (Primack and Miao 1992). Additional site restrictions such as local climate during dispersal and establishment, microsite availability and competition from early establishing vegetation can also hinder the success of tree establishment from seed (Primack and Miao 1992, Kokkonen et al. 2018, Landhäusser et al. 2019). Due to the limitations of natural regeneration, the direct planting of tree seedlings has been utilized as a highly effective method to recreate closed canopy conditions (Parrotta et al. 1997, Macdonald et al. 2012).

The successful establishment of planted seedlings is dependent on seedling quality and initial site conditions (Landhäusser et al. 2012). Edaphic conditions at the time of planting can hinder the establishment of planted seedlings due to poor soil chemical and physical characteristics (Andersen et al. 1989, Bedford and Sutton 2000). Forestry operations have successfully utilized various site preparation techniques such as altering the soil physical structure and vegetation management to improve site edaphic conditions prior to tree planting (Bedford and Sutton 2000, Ewing 2002, Sloan and Jacobs 2013).

1.3 Interactions of climate, topography and substrate type and their importance in forest reclamation

In natural forest systems, the spatial distribution and heterogeneity of available resources at large (landscape) and small (microsite) scales contributes to the development and function of terrestrial ecosystems. Site heterogeneity acts as a driver for forest and vegetation diversity, as a range of soil and climatic conditions are available for vegetation establishment and growth (Bratton 1976, Ricklefs 1977, Palmer 1991). Key drivers of heterogeneous abiotic and biotic conditions in natural systems include climate, disturbance, soil parent materials, vegetation communities, topography and the interactions of these factors (Harper et al. 1965, Beatty 1984, Lundholm and Larson 1998). Alterations to edaphic and site physical and chemical conditions at small scales result in the formation of different microsites. A common example of a forest disturbance which contributes to microsite heterogeneity is windthrow, where microtopographic variation is increased by the formation of pits and mounds from downed trees (Putz et al. 1983, Beatty 1986, Sass et al. 2018). Variation in available microsite conditions initiates changes to the vegetation community and can alter the growth and productivity of vegetation colonizing the area (Nichols et al. 1998). Microsite availability contributes to forest regeneration by providing areas of different exposure to abiotic conditions, offering alterations to soil physical and chemical conditions which can better meet the growing requirements of specific vegetation (Harper et al. 1965, Beatty 1984, Peterson et al. 1990, Brown and Naeth 2014, Sass et al. 2018). In recently formed clearings on natural and reclaimed sites, increased variety of microsites formed by microtopographic variation has been demonstrated to assist with the capture and germination of locally dispersed seeds (Biederman and Whisenant 2011, McGrath et al. 2012, Frouz et al. 2018). Overstory tree canopy development is also affected by microsite availability as seedling establishment can be influenced by the formation of microsites with varying edaphic conditions, contributing to alterations in tree growth and stand structure in natural forest settings (Gray and Spies 1997, Vodde et al. 2010).

Introducing microtopographic variation to post-harvest sites in forestry settings has been utilized as a method to improve the establishment and growth of planted tree seedlings by altering the physical structure of surface soils through mechanical site preparation (Bedford and Sutton 2000, Ewing 2002, Mc Carthy et al. 2017). One such site preparation method is mounding, where machinery is used to form pits and small hills (20-30cm tall) that create a range of tree planting positions (Natural Resources Canada 2017). Mounding offers microsites that vary in aspect, elevation, and exposure to mineral soil due to the mixing of surface and shallow mineral horizons during mound formation (Sutton 1993, Heineman et al. 1999, Löf et al. 2006, Mc Carthy et al. 2017). Due to the range of created microsite conditions, mounding treatments have been employed to increase the available planting positions on sites where growth limiting factors such as excess soil moisture or reduced soil temperature negatively affect the establishment of planted seedlings (Bassman 1989, Hawkins et al. 1995, Macadam and Bedford 1998). In addition to promoting natural and planted tree establishment, mounding treatments have demonstrated a lasting effect of improved tree growth on the landscape (Hawkins et al. 2006, Lieffers et al. 2019).

1.4 Increasing microsite availability on mine reclamation sites

Reclamation sites should lead to the recreation of self-sustaining ecosystems (Devito et al. 2012) capable of maintaining ecosystem services and function that are characteristic to that ecotype. Following surface mining, the reclamation process is initiated by creating topographic features representative of the area and reconstructing the landscape using overburden and stockpiled materials. Landscape scale topographic characteristics such as relief and aspect are critical to the formation of reclamation sites and will influence local abiotic conditions. Variations in topography contribute to the formation of soils and their properties (Manning et al. 2001), and influence colonizing vegetation on reclamation sites (Martín-moreno et al. 2013). Additionally, topographic features and the materials they are composed of will affect the redistribution of water and water soluble nutrients on the site (Nicolau 2003, Devito et al. 2012). Coversoils and underlying materials used on reclamation sites will heavily impact moisture availability for establishing vegetation (Devito et al. 2012). Thus, the inherent physical and chemical characteristics of coversoils combined with site topographical characteristics are highly important to the formation of microsites and diverse soil edaphic conditions.

Typically, the coversoil caps used for forest restoration are deeper than those in agricultural settings (Mackenzie 2011), however additional considerations must be made when using coversoils as a reclamation amendment due to the structure of the created environment. Reclaimed mining sites often struggle to replicate natural soil conditions due to the application of overburden material and the mixing of topsoil and subsoil materials used as coversoils

(Macdonald et al. 2012). For these reasons, reclamation sites can be described as novel ecosystems as these soil conditions were not previously found on the site (Hobbs et al. 2009). To combat these issues, salvaged coversoils can be applied in layers to better mimic natural systems where conditions change moving through the soil profile (Mackenzie 2011, Macdonald et al. 2015a). However, this is challenging to achieve in operational settings as soil horizons have fluctuating thicknesses, so multiple soil horizons may be salvaged at the same time. Salvaging methods, combined with stockpiling, transportation and placement on the reclamation site cause mixing of the salvaged soil horizons, resulting in the formation of coversoil blends (Naeth et al. 2013).

The two common types of salvaged soil used for reclamation in the AOSR (FFM and PMM) have different chemical and physical properties which may influence their ability to support vegetation based on site abiotic conditions. Salvaged FFM contains thin LFH layers (5 – 10cm) and a valuable seed propagule bank sourced from plant species native to upland forests (Mackenzie and Naeth 2010, Naeth et al. 2013, Macdonald et al. 2015a, Melnik et al. 2017, Dhar et al. 2018). The chemical composition of FFM cover soils supports the establishment of vegetation due to higher macronutrient concentrations which may be limiting on reclamation sites, such as extractable potassium and phosphorus (Mackenzie and Naeth 2010, Naeth et al. 2013, Brown and Naeth 2014). Peat mineral mix cover soils are sourced from lowland forests and are salvaged to depth of approximately 3 m to reach mineral soils. These lowland soils are dominated by a thick organic soil layer formed by the decomposition of peat mosses (*Sphagnum* sp.) and sedges (*Carex sp.*) (Government of Alberta 2016), and have greater water holding characteristics compared to FFM based coversoils (Walczak et al. 2002, Pinno and Errington 2015, Rezanezhad et al. 2016). The high organic matter content of PMM soils contributes to this increased water holding capacity as pore sizes shrink during decomposition of organic materials and drying out of the substrate, creating numerous capillary pores that reduce water and nutrient movement through the soil profile (Rezanezhad et al. 2016). The chemical characteristics of PMM and peat based coversoils vary based on the environment from which they were salvaged, but can generally be described as having a greater C:N ratio and lower macronutrient availability compared to FFM coversoils (Mackenzie and Naeth 2010, Naeth et al. 2013, Brown and Naeth 2014). The propagule bank contained within PMM based soils is reflective of its salvage location and contains a greater number of lowland or moisture loving forest species than FFM coversoils

(Melnik et al. 2017). Although both FFM and PMM based soils have inherent benefits for the successful establishment of vegetation on reclamation sites, the choice of coversoils used is limited to the characteristics of the environment surrounding the disturbance area. Much of the area surrounding industrial disturbance in the AOSR are dominated by lowland forests (Natural Regions Committee 2006), making PMM based coversoils readily available in the area.

Coversoil properties, placement and dispersal methods will contribute to microsite heterogeneity found on reclaimed sites (Macdonald et al. 2015a). To further increase the variety of microsite conditions, reclamation practitioners should avoid contouring or smoothing coversoils following placement. Increasing the microtopographic variation of coversoils increases the range of soil edaphic conditions, leading to small spatial scale (< 1m) alterations in soil temperature, moisture, and nutrient regimes (Bruland and Richardson 2005, Macdonald et al. 2015a). Several studies have increased microsite heterogeneity during site construction through the addition of coarse woody debris (Kwak et al. 2015, Pinno and Gupta 2018) and microtopographic variation (Gilland and Mc Carthy 2012, 2014, Frouz et al. 2015, 2018), but many of these studies have focussed on the effects of microsite variation on vegetation recruitment and establishment, soil forming processes, or soil faunal response in wetland and agricultural settings (Zedler and Zedler 1969, Mcginnies et al. 1976, Bruland and Richardson 2005, Moser et al. 2009, Mackenzie and Naeth 2010, Brown and Naeth 2014, Gilland and Mc Carthy 2014, Schott et al. 2014, Frouz et al. 2015, Lieffers et al. 2017, Melnik et al. 2017). However, a knowledge gap currently exists on the growth responses of planted tree seedlings and the recruitment of naturally regenerating trees to various created microsite conditions on upland boreal forest reclamation sites.

1.5 Research Objectives

The objective of this thesis was to evaluate the growth performance of planted tree seedlings on three different microtopographic treatments created at an operational scale reclamation site. This study also aimed to quantify differences in above and belowground morphological characteristics in response to microsite planting positions on microtopographic features, and to compare growth responses on features composed of two different salvaged soil types. The experience gained from this study will be used to influence the creation of reclamation sites, specifically providing insight on coversoil placement and microsite tree planting techniques used on upland boreal forest sites.

In Chapter 2, the three year growth responses of planted trembling aspen (*Populus tremuloides* Michx.), jack pine (*Pinus banksiana* Lamb.) and white spruce (*Picea glauca* Moench.) seedlings were assessed in response to three different surface microtopographic treatments (control, ridged and hilled). These treatments were mechanically created by manipulating coversoils placed on two research sites (south-facing and east-facing) of a large overburden structure. Additional data was collected on the natural colonization of tree and shrub species on the site, which was used to compare the recruitment and establishment of naturally regenerating woody vegetation between microtopographic treatments and research sites.

In Chapter 3, the influence of specific microsite planting positions (different micro-aspects and micro-elevations) and coversoil types on the performance of planted trembling aspen, jack pine and white spruce were investigated. To further investigate how trees explore belowground resources from these microsites, the root systems of trembling aspen were compared among microsites and coversoil material types.

Chapter 2: The impact of surface microtopographical variation on early tree seedling establishment and growth in forest reclamation

2.1 Introduction

Spatial heterogeneity plays an important role in the function of terrestrial ecosystems, providing a variety of conditions and microsite types in space and time. This variability acts as a driver for plant species diversity (Lundholm and Larson 1998; Bellingham & Richardson 2006) providing a range of conditions suitable for the establishment and growth of a variety of plants. Abiotic and biotic conditions and resource availability, such as growing space, soil nutrients, and solar radiation change as a result of topography, soil substrates, pre-existing plant communities, disturbance regimes, climatic and edaphic processes, and their interactions (Zedler and Zedler 1969, Bratton 1976, Beatty 1984, Fowler 1986, Zenner et al. 2007, Moser et al. 2009). For example, in natural systems microsite positions can be created by decaying coarse woody materials, tipped trees, and other small scale disturbances which produce various microtopographic positions and substrate types (Cornett et al. 1997). Microsite location and associated conditions can influence the establishment and growth of particular species by providing specific growing conditions. While plant-microsite relationships have been investigated in many studies in natural ecosystems (eg. Harpet et al. 1965; Mcginnies et al. 1976; Loneragan & Moral 1984), few have explored the role of microsite availability in restoration of heavily disturbed areas. Of those, most studies have focused on differences in vegetation establishment and seed germination based on microsite position in wetland and agricultural settings (Zedler and Zedler 1969, Eriksson and Erlhén 1992, Peterson and Peterson 1992, Hough-Snee et al. 2011, Gilland and Mc Carthy 2014, Lieffers et al. 2017). However, there is little information of the impact and vegetation responses of planted trees and colonizing vegetation to microsite conditions on upland forest restoration sites.

Re-establishment of a tree canopy following industrial disturbance can occur via natural dispersal from seed of native tree species growing near the disturbance (i.e. natural regeneration). However, the success of natural regeneration from seed is dependent on a range of conditions, such as seed viability and availability, dispersal, and the proximity to the disturbance (Primack and Miao 1992). Further, the availability of appropriate microsites, weather conditions during dispersal and early establishment, and competition from other colonizing species are crucial to seedling success (Evans et al. 2013, Bockstette et al. 2017, Frouz et al. 2018, Kokkonen et al. 2018, Landhäusser et al. 2019). Due to the limitations associated with passive forest recovery using natural regeneration, the restoration of a forest canopy on reclamation sites often relies on the planting of tree seedlings (Macdonald et al. 2012). Out-planting success of seedlings is dependent on numerous factors related to both seedling quality and site characteristics, which can be influenced by site preparation (Mattsson 1996; Landhäusser et al. 2012). Forest management practices have utilized site preparation techniques to improve initial growing conditions by enhancing rooting space and reducing competition for planted seedlings (Lieffers and Beck 1994, Bedford and Sutton 2000, Löf et al. 2006, Landhäusser et al. 2019). Such site preparation techniques include soil tilling, disk trenching, and the formation of small mounds (Sutton 1993). In addition to site preparation, careful consideration should be employed when selecting seedling planting locations. Microsite positions will vary with edaphic conditions (e.g. water and nutrient supply, air and soil temperature) (Bruland and Richardson 2005). Selecting appropriate planting microsites that will provide suitable growing conditions for the seedlings is important and will depend on prevailing site conditions on a forest reclamation site (Titus and del Moral 1998, Grossnickle and Macdonald 2017).

Reclamation areas provide unique opportunities to explore the individual drivers of microsite conditions, such as climate and substrate type, independent of the pre-existing conditions found on natural sites. Microtopographical conditions of natural sites are indirectly confounded by long-term legacy effects of climate and topography, which have affected edaphic and biotic conditions over millennia. These effects are absent in newly reconstructed reclamation areas, where landforms and sites are reconstructed with the same soil materials. However, unlike natural systems, reclamation areas often lack microsite heterogeneity due to operational practices such as contouring and levelling during land and soil reconstruction. By introducing variation on a reclamation landscape by increasing microtopography and/or by increasing surface soil heterogeneity using mechanical means and different substrate types, the effects of these manipulations on site conditions during early forest establishment can be explored in more detail.

Based on current literature regarding plant responses to microsite variation in natural and forestry settings, it was hypothesized that planted species growth and the establishment of naturally regenerating trees and shrubs would be influenced by the presence of microtopographic variation. The objectives of this research were to: (1) examine the impact of surface soil microtopography on the early growth of planted trembling aspen, jack pine and white spruce seedlings, and (2) measure the impact of mechanically created microtopographic variation on the natural colonization and regeneration of trees and shrub species from seed.

2.2 Materials and Methods

2.2.1 Study area

Research was conducted at the Canadian Natural Resources Limited Albian Sands mine located 70 km north of Fort McMurray, Alberta, Canada (57°15'N, 111°23'W). This mine is located within the Central Mixedwood subregion of the boreal forest (Natural Regions Committee 2006). Upland forests in this region are typically mixed stands of trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss) on mesic sites, or pure stands of jack pine (*Pinus banksiana* Lamb.) on xeric sites. Depending on the site location and overlying forest type, the soils are classified as Luvisolic and Brunisolic, which can accumulate organic horizons (LFH layers) of varying thickness (Natural Regions Committee 2006; Soil Classification Working Group 1998). Lowland (wetland) forests commonly contain black spruce (*Picea mariana* (Miller) B. S. P.) and tamarack (*Larix laricina* (Du Roi) K. Koch) and have developed on poorly drained soils. These conditions result in the accumulation of peat material, which is composed of partially decomposed vegetation consisting primarily of sphagnum moss or sedges (Carex sp.), above the mineral horizons (Government of Alberta 2016). Climate in the region is cold with an average annual temperature of 1 °C, with monthly January and July temperatures of -17.4 °C and 17.1 °C, respectively (Environment Canada 2018). Average annual precipitation is 418.6 mm in the region (Environment Canada 2018).

2.2.2 Study design and site construction

Within the mine, the two research sites (each 5ha) were located on a large overburden dump (hill landform, approximately 350 ha surface area) constructed from lean oil sands overburden material. One site (South) was located on the south-facing slope and one site (East) on the east-facing slope (Figure 2-1a). The slope gradient was approximately 36% for both sites. On each site, five blocks (each 100 × 100 m) were set up adjacent to one another, each with a 5 m buffer. Each block was divided into three treatment areas (33 × 100 m), with each being randomly assigned one of three microtopographic treatments (control, ridged, and hilled (see below)) forming a complete randomized block design (Figure 2-1b).

To reclaim the overburden structure, salvaged forest floor material (FFM) and peat mineral mix (PMM) were used to support plant growth and establishment. Forest floor material is composed of the L, F, H organic layers, and the mineral A and B horizons to a depth of approximately 30 cm. The salvaged FFM material used in this study had shallow organic LFH horizons which were approximately 5 cm thick. Salvaged PMM can have varying proportions of mineral soil and peat components depending on salvage depth. Generally, PMM can be characterized by having a high organic matter content.

Site preparation began with leveling the overburden and capping it with 35 cm of PMM in the summer of 2014. An additional layer (15 cm) of FFM material was applied on top of the PMM material to form a 50 cm coversoil cap over the overburden material (Figure 2-2a). Both the PMM and FFM were salvaged in April 2014 and stockpiled for a short period (< 3 months) until application in fall 2014 using a D6 Caterpillar® bulldozer. The control treatment is similar to current and common operational practices, as there is no significant microtopographic variation. The ridged treatment was constructed by also applying a 15 cm layer of FFM over top of the PMM layer (Figure 2-2a). Instead of leveling the soil surface, large parallel soil surface ridges running perpendicular to the slope were created using the tracks of a D8 Caterpillar® bulldozer. The ridged treatment was created in early spring (March 2015) while the underlying overburden and PMM layer were still frozen, but the surface FFM had thawed. This allowed the formation of ridges but minimized compaction of subsurface layers. The created ridges were 0.4 to 0.8 m tall, approximately 1.5 m wide, and were spaced 1 to 2 m apart (Figure 2-2b). The hilled treatment was constructed in the winter when the base PMM layer was frozen. Forest floor material and PMM coversoils were randomly selected using a D6 Caterpillar® bulldozer and pushed downhill from the upper slope position of the overburden landform to their final position. Hills were loosely pilled in off-set rows approximately 1.5 m apart and measured 3.5 m wide by 5 m long and 1.5 m tall (Figure 2-2b). Following soil placement, 1-year old seedlings of three native tree species (trembling aspen, white spruce, and jack pine) were randomly planted across the site at a density of 3200 stems per hectare in a 60-20-20 mixture, respectively.

2.2.3 Measurements

Influence of microtopographic treatments on tree seedling growth and establishment

To assess tree performance for the first research objective, belt transects (90 m long by 2 m wide) were created in each microtopographic treatment in all blocks on both slopes. Data was collected on all trees found within the transects and identified species, seedling height, root collar diameter (RCD), and microsite position (when applicable). This data was also collected for all naturally regenerating trees and shrubs found within each transect. Initial measurements were completed shortly after planting in May 2015, with the first growing season response being measured in August 2015 on the south-facing slope. Transect data collection occurred in June 2016 for initial growing season measurements on the south-facing slope only, and on both slopes in August 2016 and 2017. Transect start and end points were marked for replication in subsequent growing seasons. Tree growth measurement techniques were consistent throughout sampling periods. Relative height growth (*(final height – initial height) / initial height*) from 2015 to 2017 on the south slope and 2016 to 2017 on the east slope was calculated to compare the influence of microtopographic treatments among the planted tree seedlings.

Tree growth responses at the microsite scale

Tree measurements taken from transects were used to assess the influence of microsite position on seedling growth in the ridged and hilled treatments. Microsite positions were defined as toe, mid and crest in the ridged treatment, and between hill, toe, mid and crest in the hilled treatment. Microsite growth responses were only compared for trembling aspen due to its abundance on both research sites and its presence across microsites within transects.

In August 2017, additional data on microsite descriptions was collected on both research slopes. Microsite descriptions were created for the ridged and hilled treatments by recording microsite position (Figure 2-2c) in 25 cm increments along transect lines. This data was used to characterise the availability of microsite types across treatments, and to calculate a microsite preference values for naturally regenerating trees and shrubs.

2.2.4 Statistical analyses

All statistical analyses were executed in R Software (v 3.4.3, R Core Team 2018). Prior to analysis, all datasets were tested to ensure that assumptions of normality and homogeneity of variances were not violated prior to running analysis of variance (ANOVA) tests, and appropriate transformations were made to meet those assumptions when necessary. Effects were considered significant at $\alpha = 0.05$; post-hoc least-squares means tests with Holm's method for p-value adjustment were performed for significant main effects and interactions.

Statistical assessment for tree growth and establishment

Analysis of seedling responses (height, RCD and relative growth) to the microtopographical treatments were completed separately for each research site due to the delay in planting. Naturally regenerating trees and shrubs were analyzed separately from planted tree seedlings to ensure tree measurement comparisons were being made with planted seedlings only. A one-way ANOVA was used to compare average tree height and RCD for each species between microtopographic treatments on both research sites. A two-way ANOVA was used to compare relative height growth among tree species and to assess if responses to the microtopographic treatments differed among species. When normality and homoscedasticity violations existed, data was transformed using $\log_{10}$, square root or Box-Cox transformations from the *car* and *geoR* packages (Fox & Sanford 2011; Ribeiro & Diggle 2016). When transformations failed to meet the assumptions of normality and homoscedasticity, Welch's ANOVA for non-parametric testing or weighted means comparisons were completed. Linear and linear mixed effect models from the *nlme* R package (Pinheiro et al. 2018) were used depending on the presence of a significant random block effect. Type III sum of squares was used when significant interaction terms were found, and when there was no significant interaction the term was removed from the model and Type II sum of squares was used.

The average number of individuals that established via natural regeneration on the reclamation site were separated into two functional groups (tree and shrub species) and were compared among treatments and research sites, since both sites were established at the same time. Natural regeneration counts were compared using the glmmTMB package in R to account for overdispersion of data (Brooks et al. 2017). Model selection was based on AIC value comparisons from the glmmTMB models. This method was used to evaluate the influence of research slope aspect and surface microtopographic treatment on regeneration counts, and the influence of hill material type on numbers of natural regeneration. Natural regeneration microsite preference values were calculated using the following formula (Landhäusser et al. 2010):

$$Preference_{microsite} = \frac{(Number\ seedlings\ on\ microsite\ position\ x)/(Total\ number\ \ of\ seedlings)}{(Number\ \ of\ microsite\ positions\ x)/(Total\ number\ \ of\ microsite\ positions)}$$

Preference values were calculated for regenerating trembling aspen and shrubs due to their abundance on the site. To reduce statistical variation between microsites, counts of trembling aspen and shrubs were combined when calculating preference values. Trembling aspen and shrubs have similar methods of seed dispersal and seed weight which reduces ecological bias regards to natural regeneration, allowing for preference value comparisons to be made.

On hilled treatments, preference values were grouped for toe and between hill positions. Additionally, mid-slope preference values on the hilled treatment at north and east hill micro-aspects were grouped and referred to as mid-low input, and south and west micro-aspects were grouped and referred to as mid-high input microsites. Ridged treatment microsites were defined as crest, mid-slope (mid), or toe positions.

Two-way ANOVAs were completed to analyze the influence of microsite position and research site (East or South) on natural regeneration preference values. Log_{10} transformations with the addition of a constant ($x + 1$) were completed for preference values to meet the assumptions of normality and homoscedasticity for two-way ANOVAs. Post hoc comparisons were completed with Holm's method for p-value adjustment.

2.3 Results

2.3.1 Tree growth response to microtopographic treatments

Average seedling height and RCD in 2017 was used to assess current tree growth responses to the microtopographic treatments; the two sites were analyzed separately and differences in responses were only compared qualitatively, as both sites were planted in two different years (see methods). On the South site (i.e. south-facing slope), trembling aspen height and RCD were significantly influenced by microtopographic treatment ($p < 0.05$ and $p < 0.001$ respectively) (Figure 2-3). Aspen height and RCD were greatest on the hilled treatment (Control – height: 122.5 cm, RCD: 12.5 mm; Ridged – height: 131.5 cm, RCD: 15.0 mm; Hilled – height: 161.7 cm, RCD: 22.0 mm). Jack pine height was not impacted by the microtopographic treatments; however, RCD was greater on the hilled treatment ($p < 0.005$) (Figure 2-3) (Control – RCD: 9.6 mm; Ridged – RCD: 12.3 mm; Hilled – RCD: 14.5 mm). Similarly, white spruce RCD was greater on the hilled treatment ($p < 0.05$) (Control – RCD: 10.2 mm; Ridged – RCD: 12.7mm;

Hilled – RCD: 13.7 mm), but its height was not affected by the treatments. On the East site (i.e. east-facing slope), only the height of jack pine was affected by microtopographic treatments ($p < 0.05$), where pine was taller on the ridged treatment compared to the control (Figure 2-4) (Control – height: 37.3 cm; Ridged – height: 40.3 cm; Hilled – height: 39.7 cm). Root collar diameter of all three species was not affected by the microtopographic treatments.

On the South site, relative height growth was affected by the microtopographic treatments ($p < 0.001$) and species ($p < 0.001$), but species did not differ in their response to the treatments (i.e. no treatment by species interaction). Relative height growth of all species was greatest on the hilled treatment (2.0 cm/cm) compared to the control treatment (1.5 cm/cm) ($p < 0.01$), but no difference was found between the hilled and ridged (1.7 cm/cm) or the control and ridged treatments (Figure 2-5a). The relative height growth of aspen (3.4 cm/cm) was greater than spruce (0.6 cm/cm) and pine (1.2 cm/cm) (both $p < 0.001$), and the relative height growth of pine was greater than spruce ($p < 0.001$) (Figure 2-5b). On the East site, relative height growth was affected by the microtopographical treatments; however, the response was species specific (treatment × species interaction, $p < 0.01$) (Figure 2-6). While relative height growth of aspen was greater on the hilled (1.8 cm/cm) treatment compared to the control (1.0 cm/cm) and ridged (1.1 cm/cm) treatments, growth in spruce and pine was not influenced by microtopographic treatment (Figure 2-6). However, similar to the South site, overall relative height growth of aspen was greater than of pine and spruce (both $p < 0.05$).

Naturally regenerating trees and woody shrubs found across the two research sites included mostly trembling aspen and willow species (*Salix* spp.), while jack pine, white spruce, white birch (*Betula papyrifera* Marsh.), and green alder (*Alnus crispa* (Vill.) Lam. &DC.) seedlings were rare. Slope aspect impacted the natural regeneration of trees and shrubs as the average regeneration count was greater on the East site (average seedling count: 26.6) compared to the South site (average seedling count: 13.3) ($p < 0.005$) (Figure 2-7a). Regardless of site aspect, average counts of natural tree seedling establishment were influenced by the microtopographic treatments and were greater in the hilled treatment (average seedling count: 44.5) compared to the ridged (average seedling count: 14.5) and control (average seedling count: 3.2) treatments and was greater in the ridged treatment compared to the control treatment (Figure 2-7b), while average shrub regeneration was not influenced by microtopographic treatment (Control –

average seedling count: 13; Ridged – average seedling count 18.6; Hilled – average seedling count: 26) (functional type and microtopographic treatment interaction $p < 0.005$).

2.3.2 Natural regeneration and planted seedling growth in response to microtopographical position

To explore the response of planted aspen seedlings to microsite position (ridged and hilled treatment) and material type (hilled treatment only) in more detail, growth was compared among seedlings that had been planted in different microsite positions based on data collected from the transects. On the South site, aspen seedlings planted in the crest position in the hilled treatment were taller than seedlings planted between hills and in the mid-slope positions (Crest – height: 180.1 cm; Mid-slope – height:161.6 cm; Between hills – height: 147.7 cm) ($p < 0.05$) (Figure 2-8a). Aspen's RCD responded similar to height (Crest – RCD: 26.1 mm; Mid-slope – RCD: 21.2 mm; Between hills – 19.8 mm) ($p < 0.001$) (Figure 2-8b). Height and RCD were not affected by hill material type (FFM – height: 151.5 cm, RCD: 20.2 mm; PMM – height: 183.9 cm, RCD: 26.0 mm) (Figure 2-9). In the ridged treatment, microsite position had an impact on aspen RCD and was greater in the crest position (16.2 mm) compared to the mid-slope position (14.2 mm) (Figure 2-10), however height was not influenced by microsite position (Crest – height: 133.8 cm; Mid-slope – height: 126.8 cm; Toe – height: 138.7 cm) (Table A-1).

Responses for aspen were similar on the East site. There, aspen planted at the mid-slope position of hills were taller than seedlings planted between hills (Mid-slope – height: 81.8 cm; Between hills – 60.0 cm) ($p< 0.05$) (Figure 2-11a). Root collar diameter was also affected by microsite position ($p < 0.001$) and was larger at the mid-slope position (RCD: 9.4 mm) compared to trees planted at the toe (RCD: 7.7 mm) and between hill positions (RCD: 6.6 mm) (Figure 2-11b). Aspen height and RCD did not significantly differ between hill material types (Figure 2-9), and height and RCD responses were not influenced by microsite position on the ridged treatment (Appendix A-1).

Since only aspen and willows were the prevalent naturally regenerating species and have very similar seed dispersal and germination requirements, these species were combined to explore broader questions related to microsite preference (see below). The few naturally regenerated jack pine seedlings were found in toe position microsites in the ridged and hilled treatments on the East site, and only in one instance on the control treatment on the South site. Naturally regenerating white birch and white spruce seedlings were only found at the toe position of the ridged treatment on the East site. In the hilled treatment, there were significantly more naturally regenerating aspen and willow shrubs found on PMM hills compared to FFM hills ($p < 0.001$) (Figure 2-12).

Overall, in the ridged treatment, the abundance of naturally regenerating aspen and shrub species were affected by microsite position ($p < 0.001$) and were more abundant on the toe and mid-slope positions than the crest of the ridge (Figure 2-13a). This trend was seen on both the South and East sites (i.e. no microsite by research site interaction) and natural regeneration abundance did not differ between research sites. On the East site, naturally regenerating aspen and shrubs were more commonly found at the hill's toe (average seedling count: 77) compared to the other available microsites and were more common on the mid-low input microsite (average seedling count: 5.4) compared to the crest microsite (average seedling count: 2.2) (microsite × research site interaction $p < 0.05$; Figure 2-13b). On the South site, more naturally regenerating trees and shrubs were found at the toe microsite (average seedling count: 37.6) compared to all other available microsites, and the mid-low input microsite (average seedling count: 7.2) had more regenerating aspen and shrubs than the mid-high (average seedling count: 3.6) input and crest microsites (average seedling count: 3.4) (Figure 2-13b). When comparing the two research sites, aspen and shrub regeneration at the toe microsite on the East site was greater than the regeneration abundance of the toe microsite on the South site. Aspen and willow species combined had a greater preference for toe microsite positions compared to all other available microsite positions in the ridged and hilled treatments, regardless of site (Figure 2-13a, b).

2.4 Discussion

Increasing microtopographic variation on forest restoration sites improved the average growth of tree seedlings and significantly increased the establishment of naturally regenerating woody species. Despite the differences in the level of response by planted aspen, pine and white spruce seedlings to increases in microtopography, the relative height growth of all species was greatest on the hilled treatment, particularly on the South site. When comparing responses among species, trembling aspen responded strongest to increased variability of microsites than pine and spruce on both the south and east facing slopes. This difference is potentially related to the varying growth strategies seen between species as deciduous growth is typically faster than that of coniferous species. Increasing soil topography by mechanical site preparation methods in forested sites has been shown to benefit tree growth and establishment (Haeussler et al. 1999, Boateng et al. 2006, Evans et al. 2013, Fields-Johnson et al. 2014, Frouz et al. 2018). Particularly, mounding techniques have been identified to improve planted seedling growth more than other site preparation techniques for the growth of planted white spruce (Archibold et al. 2000, Boateng et al. 2006, Hawkins et al. 2006, Lieffers et al. 2019), jack pine (Sutton and Weldon 1993) and trembling aspen seedlings (Hjelm and Rytter 2018). Some reported benefits of mounding site preparation are increased soil temperature, improved soil drainage on waterlogged sites, and altered soil physical structure (Haeussler et al. 1999, Archibold et al. 2000, Boateng et al. 2006, Evans et al. 2013). The hills created in this study are somewhat similar to traditional mounding techniques utilized in forestry settings, however mounds used in forestry site preparation are typically 20-30cm tall (Natural Resources Canada 2017), which is much smaller than the created hills used in this experiment. Although the created hills are much larger, planted seedlings still benefited from the increased microtopographic variation and altered microsite conditions associated with mounding site preparation. Qualitatively comparing relative height growth trends between the East and South research sites suggests that the presence of microtopographic variation on the East site was not as influential as seen on the South site. However, Kate Melnik (2017) has shown that the two sites had similar abiotic conditions as there was no influence of research site on soil moisture, temperature, soil bulk density, or snow accumulation, suggesting that an external factor not measured in this experiment may be contributing to the differences in relative height growth patterns seen between research sites.

Greater microtopographic variation also resulted in significant increases in colonization from outside seed sources on both research sites. The hilled and ridged treatments had greater surface roughness compared to the control treatment, which is more conducive to seed capture (Frouz et al. 2018) and increases the number of microsites with higher soil moisture availability that are more suitable for tree seed germination (Landhäusser et al. 2019). Greater surface roughness creates microsites where seeds can land and remain sheltered from abiotic disturbances such as wind and sun exposure until germination, whereas low surface roughness has less protected areas, making seed germination more difficult. Additionally, the size of features created can influence seed capture from adjacent sources (Farrell et al. 2012) which may contribute to the higher numbers of naturally regenerated individuals in the hilled treatment compared to the ridged treatment. Enhancing microtopographic variation on forestry reclamation sites by using site preparation techniques, such as mounding have been linked to greater natural regeneration of conifer and deciduous tree species (Gärtner et al. 2011, Lieffers et al. 2017). Specifically, Lieffers et al. (2017) and Landhäusser et al (2019) found aspen regeneration from seed was most common on moist microsites overlying well decomposed peat substrates with high moisture holding capacity. The results of this study are congruent with previous research as natural regeneration of aspen and willow shrubs was greater on toe microsites on ridged and hilled treatments, and on PMM hills within the hilled treatment.

The increased size of hill microtopographic features generates a greater range of soil temperature and moisture gradients, as well as sheltered areas that are necessary for plant establishment (Titus and del Moral 1998, Pinno and Errington 2015). For example, trembling aspen regeneration from seed is highly dependent on microsite soil moisture availability and requires a substrate with high moisture holding capacity, such as soils with high organic matter content (Landhäusser et al. 2019). Toe positions within the research sites have overall greater soil water content (Melnik et al. 2017) than other microsites which contributes to favourable conditions for seed germination. The results of this experiment align with research that suggests tree seed germination can be enhanced based on available microsite conditions and surface roughness (Cornett et al. 1997; Landhäusser et al. 2010; Schott et al. 2014; Pinno & Errington 2015; Frouz et al. 2018). Interestingly, aspen regeneration increased significantly with the addition of microtopographic variation, while willow regeneration was not different between microtopographic treatments. Willow (*Salix* spp.) regeneration from seed is most successful on exposed mineral soil and microsites which have adequate soil moisture and unobstructed sunlight (Porter 1990). Natural regeneration results from this study suggest that conditions between microtopographic treatments were not severe enough to initiate a change in willow regeneration. This indicates that aspen regeneration from seed is more dependent on the presence of microtopography than the regeneration of the willow species found within the research area. Additionally, the results of this study show that the East site had greater numbers of naturally regenerating trees and shrubs than the South site. The closest seed source (measured to the edge of a stand of trees to the centre of the site) on the South site is approximately 200 m away and the closest seed source for the East site is approximately 850 m away. It is possible that the more moderate conditions on the East aspect site provide better conditions for seed germination than what is available on the South site.

The varying distribution of cover soils and soil physical characteristics among treatments may have also influenced seedling growth and natural regeneration responses. On the soil surface, the control treatment did not have any exposed PMM cover soil, as it was capped with FFM. The ridged and hilled treatments had exposed PMM based soil due to the methods used to create the microtopographic treatments. The ridged treatment had PMM exposure at the toe position between ridges, while on the hilled treatment all areas between hills had exposed PMM soil with the addition of hills that were composed of PMM. Soils with high organic matter content such as PMM can retain greater amounts of soil moisture compared to mineral based soils, which contribute to the increased seedling growth and seed germination experienced in this study. In addition to substrate material, soil physical characteristics influence natural regeneration and seedling growth. Methods of mechanical site preparation can influence soil compaction, as average soil bulk density was greater in the control treatment (1.45 ± 0.02 g/cm^3), followed by the ridged treatment (1.34 ± 0.02 g/cm^3), and was lowest in the hilled treatment (1.03 ± 0.02 g/cm^3) (Melnik et al. 2017). Creating the control and ridged treatments required many machine passes by the bulldozer, while the hilled treatment required much less travel from machinery as hills were formed by pushing soil over frozen ground into loose piles. Increased traffic by heavy machinery has been linked to increased soil bulk density in forestry settings on boreal forest soils found within Alberta (McNabb et al. 2001). High soil bulk density reduces plant growth by limiting root penetration (Zenner et al. 2007, Evans et al. 2013, Fields-Johnson et al. 2014) and may be a contributing factor to the differences in growth and natural regeneration responses that were observed.

This operational scale experiment has demonstrated that increasing microtopographic variation on reclamation sites via mechanical site preparation can be beneficial to forest reclamation efforts. Such benefits include increased tree seedling growth and increased recruitment of naturally regenerating trees. Maximizing the variety of microsites available by creating loosely pilled hills was the most beneficial for tree seedling growth and the recruitment of naturally regenerating trees due to increased exposure of peat-based soils with high water retention characteristics and relatively low soil bulk density compared to other mechanically formed microtopographic treatments used in this study. Although increasing microtopographic complexity has provided several benefits to forest reclamation, slope aspect and existing site conditions must be considered when applying microtopographic treatments at operational scales. Within traditional forestry settings, implementing mounding site preparation treatments can result in high operational costs (Hawkins et al. 2006), however reclamation sites provide practitioners the unique opportunity to create a site from the ground up, and in this study it was observed that the hilled treatment was the fastest treatment to create and can therefore decrease operational costs during site establishment. An additional benefit of site preparation prior to seedling planting is a lasting legacy, in which the effects of increased site microtopography have been shown to last as long as 15 years after planting (Hawkins et al. 2006, Lieffers et al. 2019). In this study, average tree growth increased or did not change compared to the control treatment with additions of microtopographic variation. Consequently, reclamation costs can be reduced by implementing hilled microtopographic treatments without jeopardizing the growth and establishment of planted tree seedlings and boreal forest reclamation.

2.5 Figures

Figure 2.5-1 (a) Aerial view of the overburden dump with the south and east research slopes outlined in red. (b) Aerial view showing one of the two research slopes and the five replication blocks with microtopographic treatments.

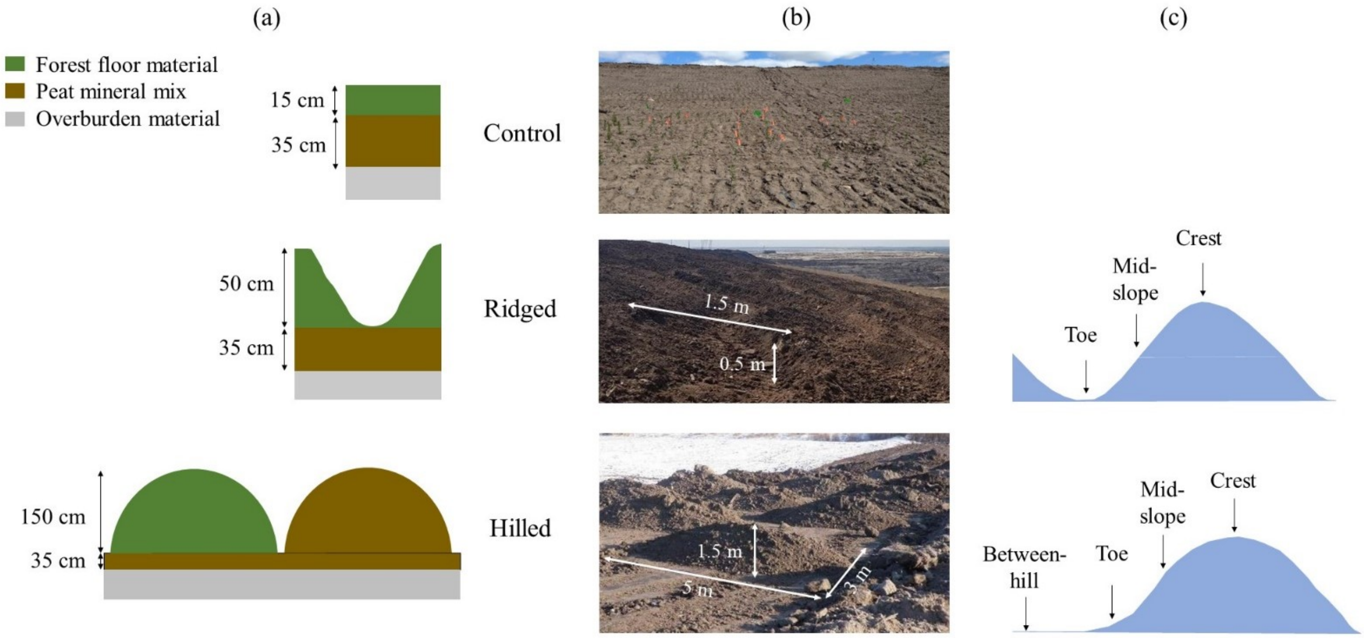

Figure 2.5-2: (a) Material layering scheme for microtopographic treatments with scale bars; (b) images of the three treatments on the research slope with scale bars; (c) microsites available within ridged (top) and hilled (bottom) microtopographic treatments.

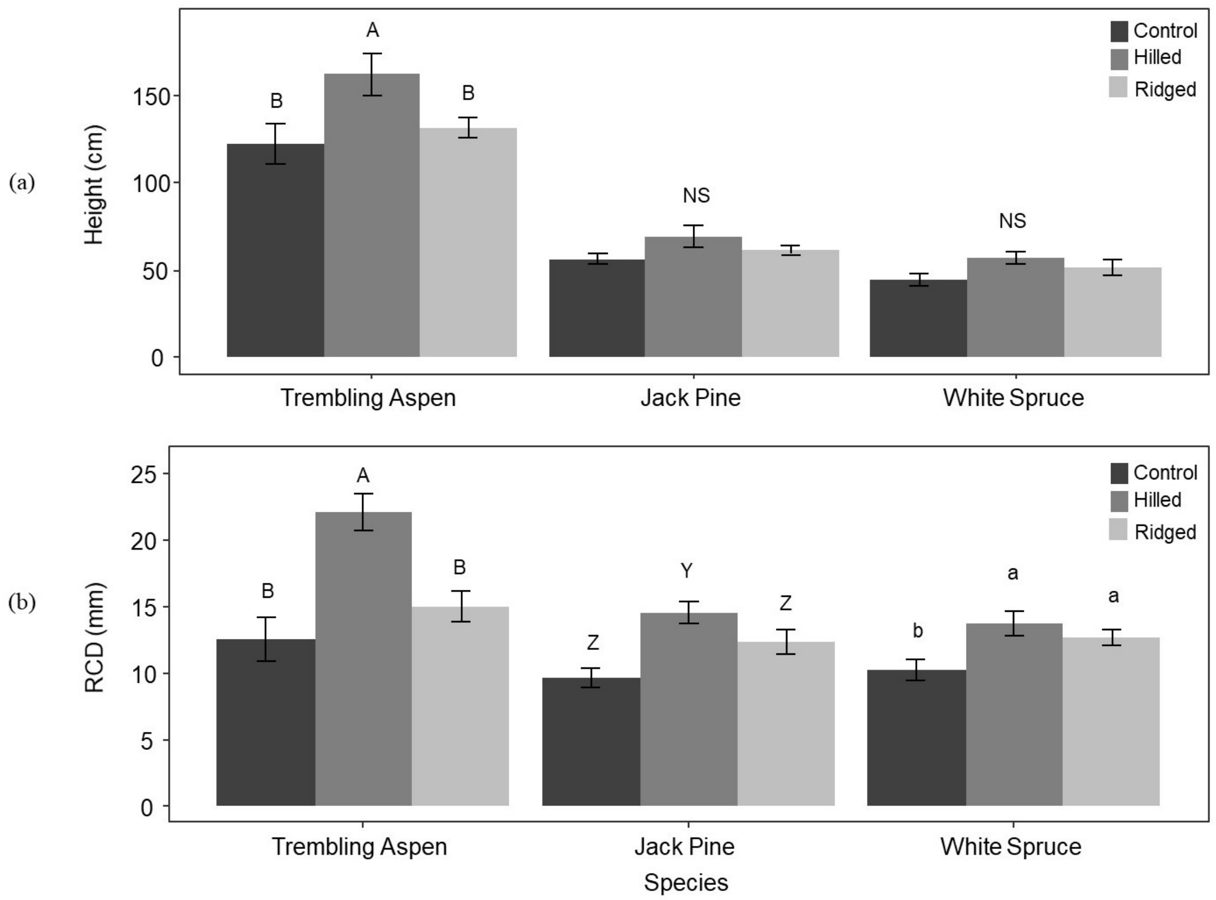

Figure 2.5-3: (a) Average height (cm) of trembling aspen, jack pine and white spruce in response to three microtopographic treatments on the South site. (b) Average RCD (mm) of trembling aspen, jack pine and white spruce in response to microtopogrpahic treatments on the South site. Tree species were analyzed separately for both analyses. Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 5$) while "NS" represents no significant difference, and bars show standard errors.

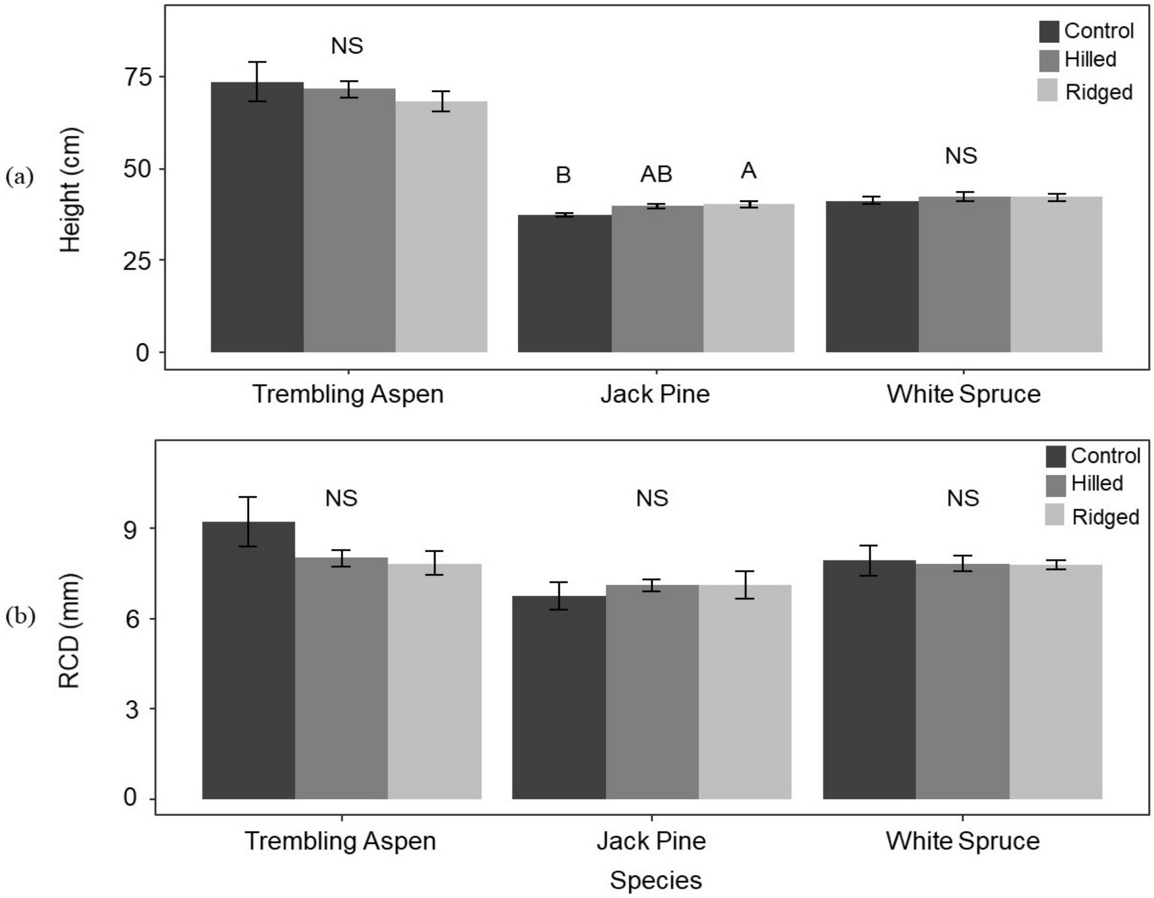

Figure 2.5-4: (a) Average height (cm) of trembling aspen, jack pine and white spruce on the East site across microtopographic treatments. (b) Average RCD (mm) of trembling aspen, jack pine and white spruce across microtopogrpahic treatments on the East site. Tree species were analyzed separately for both analyses. Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 5$), while "NS" represents no significant difference, and error bars are standard errors.

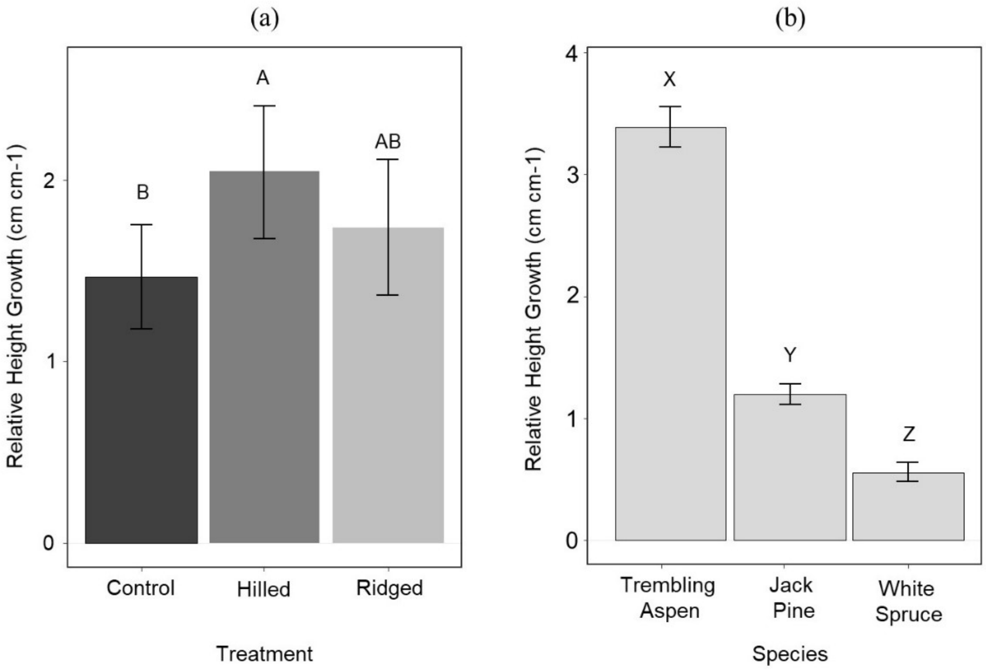

Figure 2.5-5: (a) South site relative height growth across microtopographic treatments and (b) species. No interaction exists between species and treatment. Differing letters represent statistically significant contrasts (α = 0.05, n = 5), and error bars are standard errors.

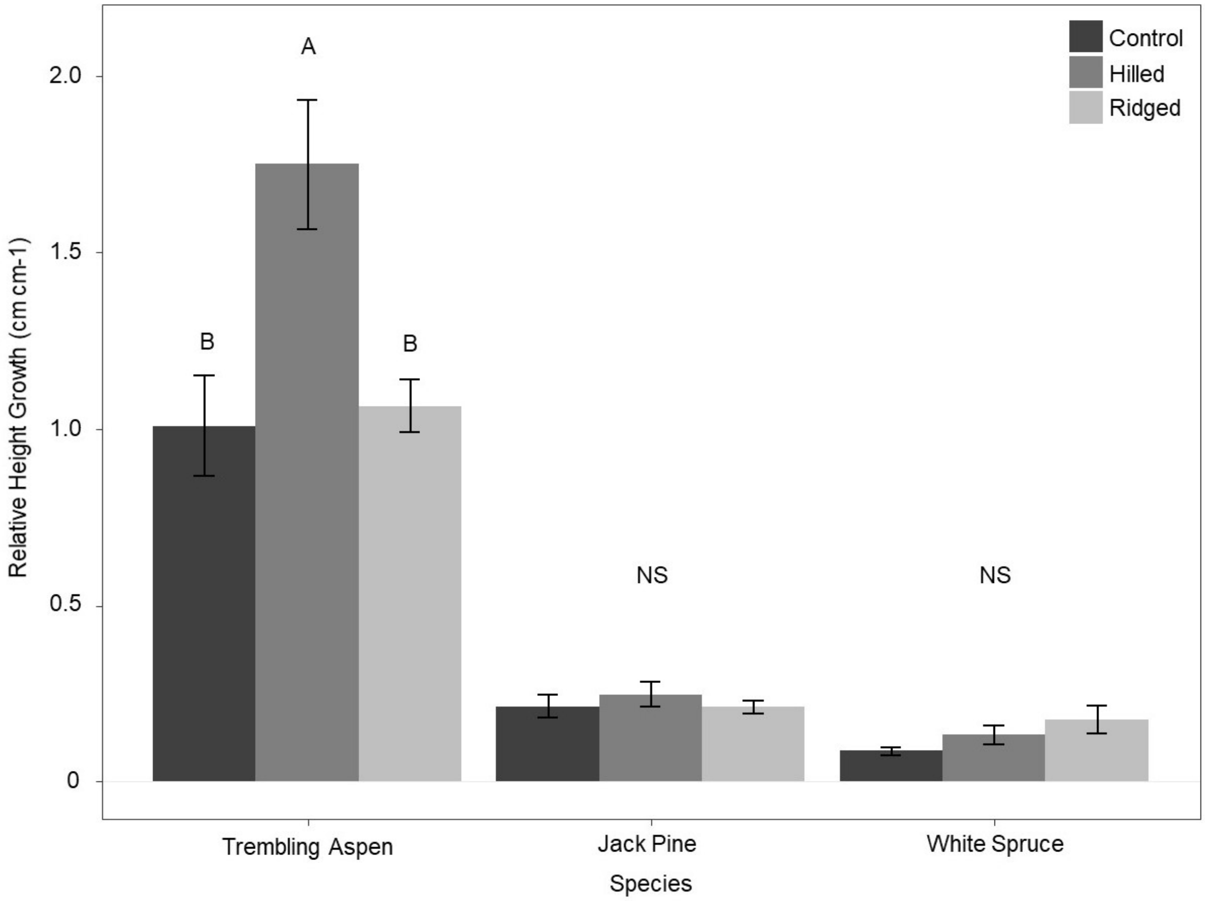

Figure 2.5-6: East site relative height growth among microtopographic treatments and species. A significant interaction exists between species and treatment ($p < 0.01$). Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 5$) while “NS” represents no significant difference, and error bars are standard errors.

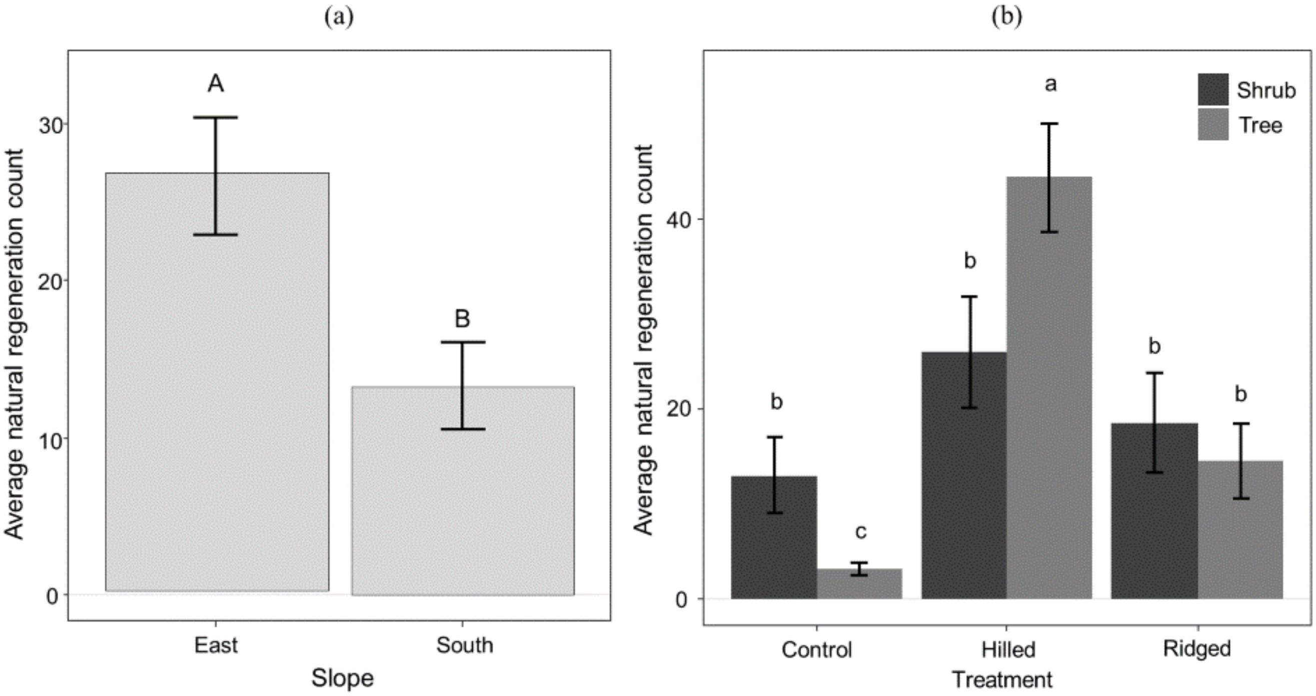

Figure 2.5-7: a) Average natural regeneration counts of woody species between research areas. b) Natural regeneration counts across treatments separated for tree and shrub species. A significant interaction exists between group (tree or shrub) and treatment ($p < 0.001$). No significant interaction exists between research site and treatment or group. Different letters indicate statistically significant contrasts ($\alpha = 0.05$, $n = 10$), and error bars are standard errors.

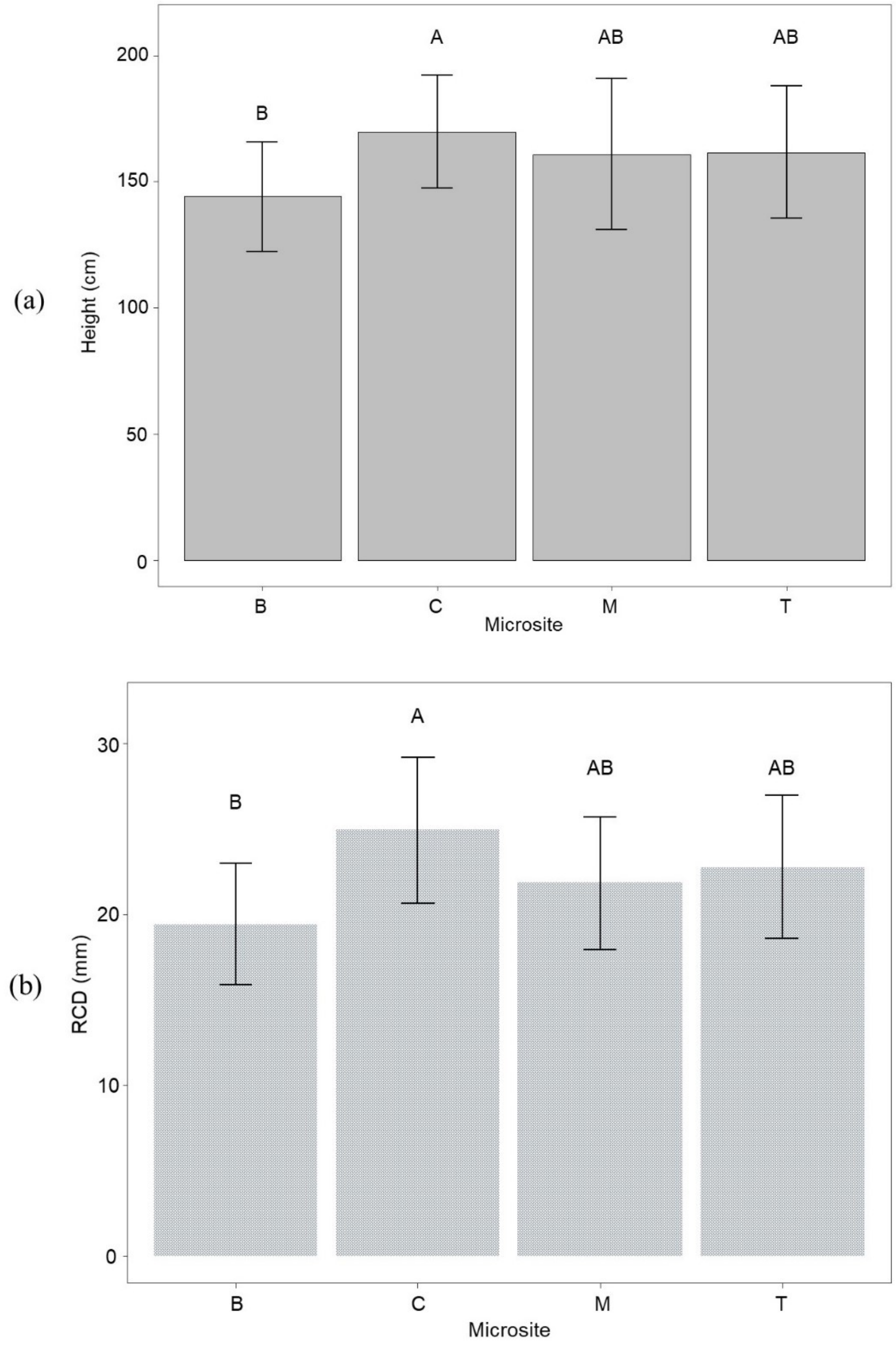

Figure 2.5-8: Average height (cm) (a) and RCD (mm) (b) of planted trembling aspen seedlings across microsite planting positions in the hilled treatment on the South site. Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 5$), and bars show standard errors. Microsite codes are: B – between hill, C – hill crest, M – hill mid-slope, and T – hill toe (see also Figure 2).

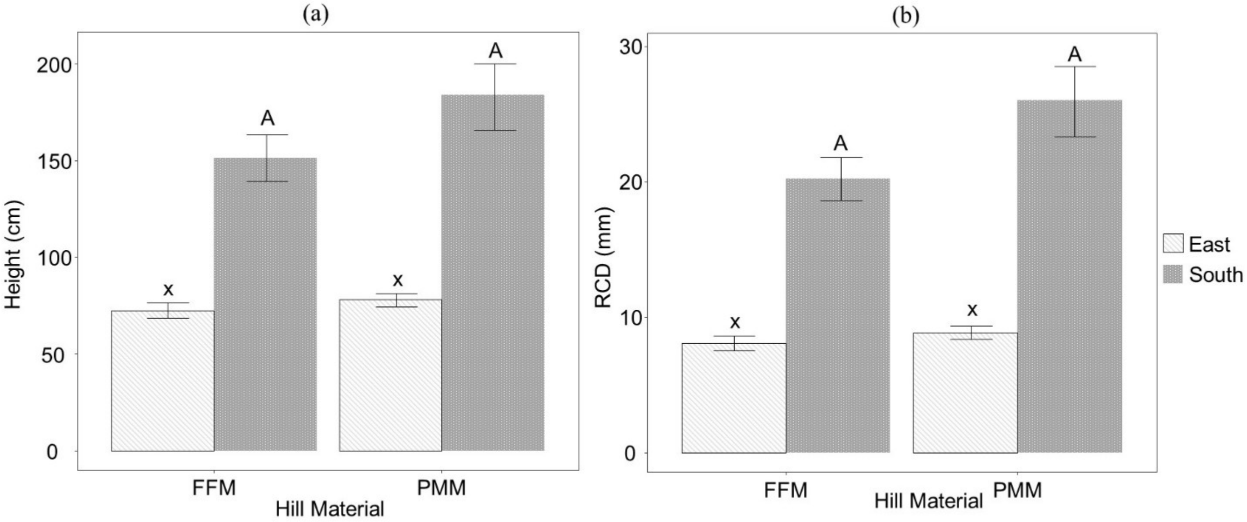

Figure 2.5-9: Average height (cm) (a) and RCD (mm) (b) of planted trembling aspen seedlings on forest floor material (FFM) and peat mineral mix (PMM) hills in the hilled treatment on East and South sites. Differences between hill material types were not statistically significant ($\alpha = 0.05$, $n = 5$), and comparisons were not made between research sites (see methods). Bars show standard errors.

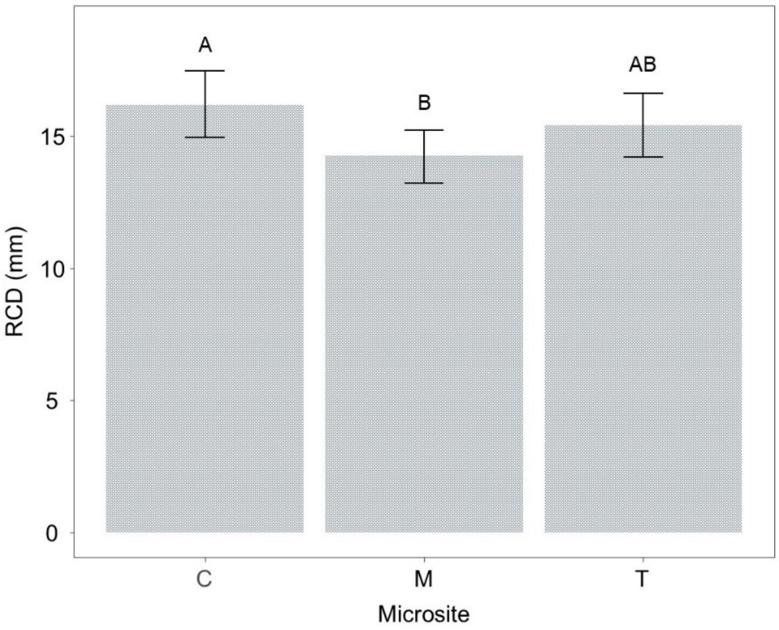

Figure 2.5-10: Average RCD (mm) of planted trembling aspen across the available microsites in the ridged treatment on the South site. Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 5$), and bars show standard errors. Microsite codes are: C – ridge crest, M – ridge mid-slope, and T – ridge toe (see also Figure 2-2).

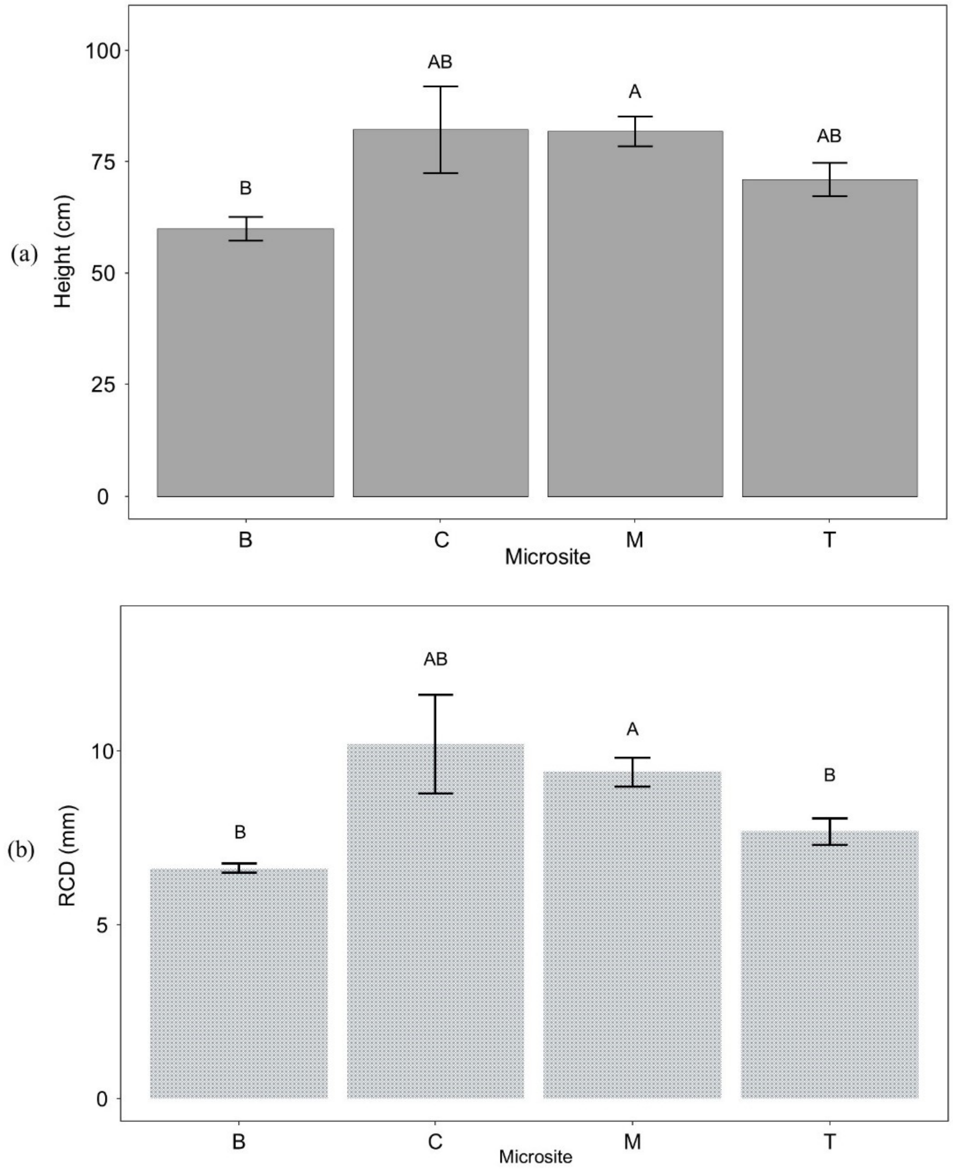

Figure 2.5-11: Average height (cm) (a) and RCD (mm) (b) of planted trembling aspen across the available microsite positions in the hilled treatment on the East site. Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 5$), and bars show standard errors. Microsite codes are: B – between hill, C – hill crest, M – hill mid-slope, and T – hill toe (see also Figure 2-2).

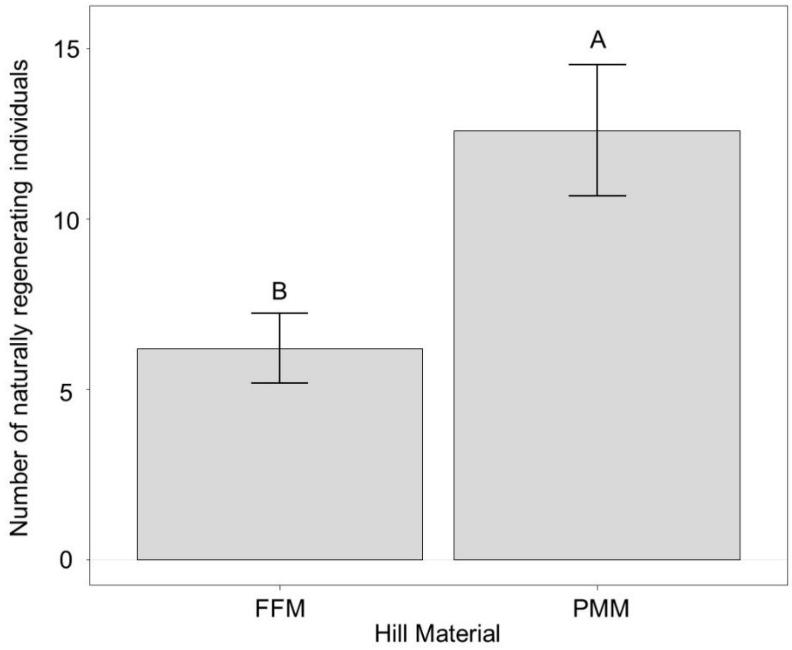

Figure 2-12: Average number of naturally regenerated seedlings on forest floor material (FFM) and peat mineral mix (PMM) hills in the hilled treatment. Differing letters represent statistically significant contrasts (α = 0.05, n = 10), and error bars are standard errors.

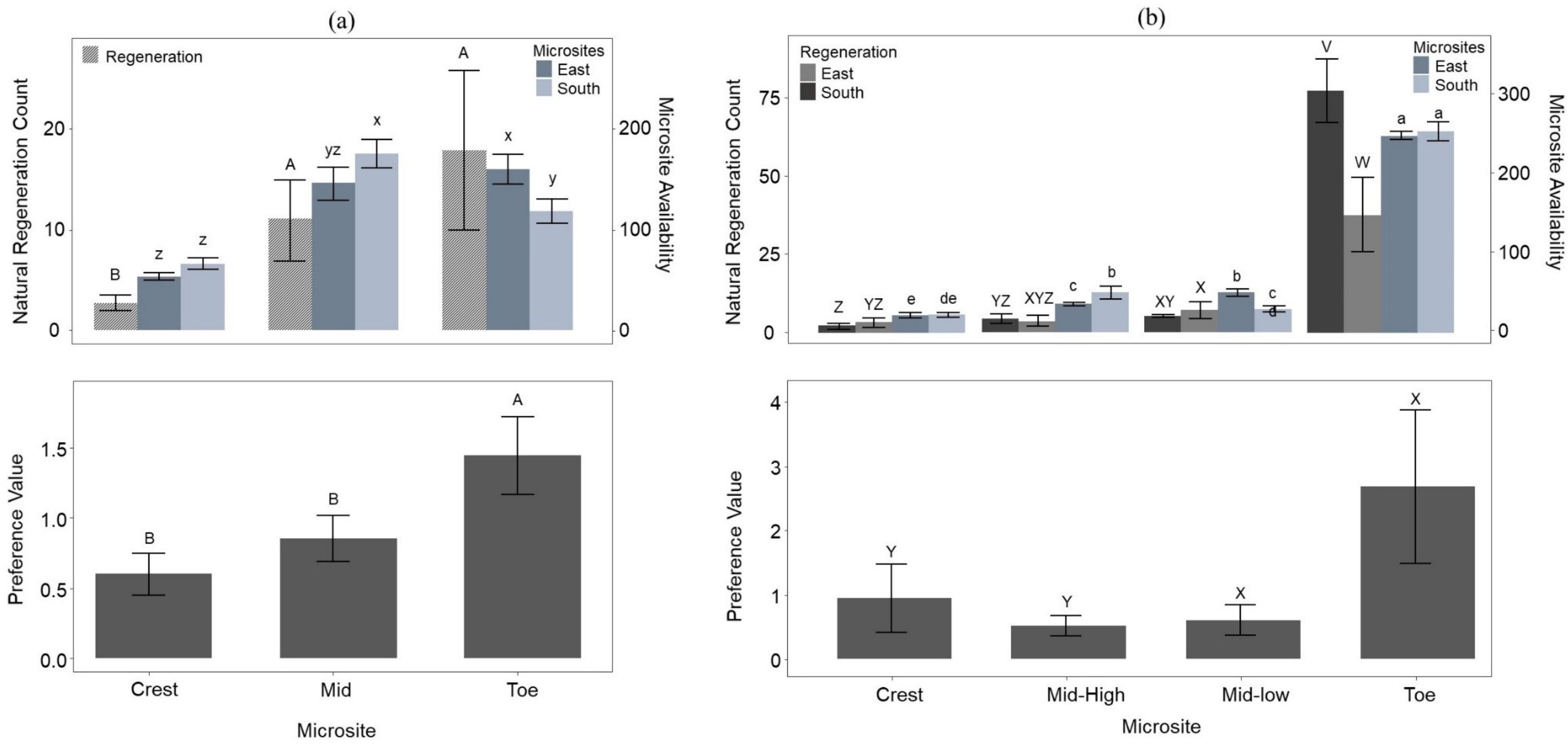

Figure 2.5-13: Average number of naturally regenerated aspen and willow (combined) across both research sites found on ridged and hilled treatments (a and b) plotted against available microsites and microsite preference value responses. Note the different scales on the y-axis between natural regeneration and microsite availability within transects. No significant interaction existed between microsite and research site for regenerated aspen and willow on the ridged treatment (a), but a significant interaction ($p < 0.05$) affected natural regeneration in the hilled treatment (b). Microsite abundance in the ridged and hilled treatments were affected by the interaction of microsite and research site ($p < 0.01$ and $p < 0.001$ respectively). No interaction existed between microsite and research site, and there was no significant affect of research site on preference values. Different letters indicate statistically significant contrasts within figure boxes ($\alpha = 0.05$, $n = 5$), and error bars are standard errors.

Chapter 3: Rooting for microsite heterogeneity: above and belowground responses of planted seedlings to microsite planting positions on created hills

3.1 Introduction

Re-establishing a tree canopy following anthropogenic disturbances, such as timber harvesting or mineral resource extraction, is a main goal when reclaiming or restoring forests (Macdonald et al. 2015a). Apart from allowing sites to naturally recover through colonization from surrounding areas (Schott et al. 2014, Frouz et al. 2015, Pinno and Errington 2015, Kokkonen et al. 2018, Landhäusser et al. 2019), the planting of seedlings is considered an efficacious approach (Nilsson et al. 2010, Macdonald et al. 2012). Although more effective than seeding, the successful establishment of planted tree seedlings is highly dependent on the seedling quality and site conditions at the time of planting (Landhäusser et al. 2012). In forestry operations, various site preparation methods are used to aid planted seedling establishment and early growth after planting (Bedford and Sutton 2000, Ewing 2002, Sloan and Jacobs 2013). Such site preparation methods, which include vegetation management approaches and alterations to soil physical conditions using mechanical site preparation treatments, intend to ameliorate the limiting site conditions for planted seedlings (i.e. growth limiting factors). Soil abiotic conditions such as moisture, nutrient availability and soil temperature are considered growth limiting factors that can be influenced by altering soil microtopography, the orientation of microtopographic features and substrate type (Archibold et al. 2000, Biederman and Whisenant 2011).

Mechanical site preparation techniques include disk trenching, bedding, and mounding (Haeussler et al. 1999, Biederman and Whisenant 2011) and are intended to reduce competing vegetation cover and mix surface soil layers to increase tree seedling access to the resources contained in mineral and organic soils (Archibold et al. 2000). Mounding has been used in the boreal forest region to create soil interfaces and microsites with different soil conditions, such as micro-aspect and microtopographical positions that affect resource availability (Sutton 1991, Sutton and Weldon 1993, Cornett et al. 1997, Boateng et al. 2006, Biederman and Whisenant 2011)). Mounds used in forest regeneration after harvesting are relatively small in scale, with piled soils settling to 20-30cm tall (Natural Resources Canada 2017). Mounding is often used on mesic and moist areas where excess soil moisture limits or on sites where competition negatively impacts the growth of planted seedlings (Landhäusser and Lieffers 1999, Mc Carthy et al. 2017).

Microsite conditions can vary in soil temperature, moisture, sun exposure, drainage, and vegetative competition (Hjelm and Rytter 2018, Wallertz et al. 2018); however, selecting specific planting microsites can alleviate or reduce the negative effects of these potential growth limiting factors. Planting seedlings at different micro-elevations or different micro-aspects of microtopographical features can also be beneficial for seedling establishment (Sutton and Weldon 1993, Gilland and Mc Carthy 2014, Hjelm and Rytter 2018, Wallertz et al. 2018), however these effects are site and species specific (Gray and Spies 1997, Collins and Carson 2004, Maher and Germino 2006, Tinya et al. 2019).

The creation of microtopographic variation has also been utilized in some land reclamation settings (Sutton 1993, Archibold et al. 2000, Nilsson and Allen 2003, Hawkins et al. 2006, Knapp et al. 2008, Bilodeau-gauthier et al. 2011, Wachowski et al. 2014, Lieffers et al. 2019), often creating larger microtopographic features than what is seen in traditional forestry operations (Gilland and Mc Carthy 2012, Frouz et al. 2018). Land reclamation sites offer a unique opportunity to explore the impact of growing conditions and microtopography independent of legacy effects, such vegetation, soil and other ecosystem structures which can confound responses. Site conditions on recently formed reclamation sites are relatively homogeneous compared to natural sites. In this study, microtopographic features were created to increase a variety of available microsite planting positions, which were used to investigate the establishment and growth responses of three tree species commonly used in land reclamation practices in the Canadian boreal forest. The aim of this research was to (1) study how planting microsite position and substrate type affect trembling aspen, white spruce and jack pine seedling above ground growth, and (2) investigate if early biomass allocation of aspen seedlings differed based on microsite position and substrate type on created microtopographic features.

3.2 Materials and Methods

3.2.1 Study area

Research was conducted at the Canadian Natural Resources Limited Albian Sands mine located 70 km north of Fort McMurray, Alberta, Canada (57°15'N, 111°23'W). This mine is located within the Central Mixedwood subregion of the boreal forest (Natural Regions Committee 2006). Upland forests in this region are typically mixed stands of trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss) on mesic sites, or pure stands of jack pine (*Pinus banksiana* Lamb.) on xeric sites. Depending on site and forests type, soils are classified as Luvisolic and Brunisolic, which can accumulate organic horizons (LFH layers) of varying thickness (Soil Classification Working Group 1998, Natural Regions Committee 2006). Lowland (wetland) forests commonly contain black spruce (*Picea mariana* (Miller) B. S. P.) and tamarack (*Larix laricina* (Du Roi) K. Koch) and have developed on poorly drained soils. These conditions result in the accumulation of peat material, which is composed of partially decomposed vegetation consisting primarily of peat mosses (*Sphagnum* sp.) or sedges (*Carex* sp.) above the mineral parent material horizons (Government of Alberta 2016). The regional climate is cold with an average annual temperature of 1 °C, with monthly January and July temperatures of -17.4 °C and 17.1 °C, respectively (Environment Canada 2018). Average annual precipitation is 418.6 mm in the region (Environment Canada 2018).

3.2.2 Study design and site construction

Within the mine, two research sites (5 ha each) were situated on a large overburden dump (hill landform, approximately 350 ha surface area) constructed from lean oil sands overburden material. One research site was located on the south-facing slope while the other was on the east-facing slope. The gradients of the slopes are approximately 36% (Figure 3-1a). Each site consisted of five research blocks (each 100 × 100 m) containing three areas (33 × 100 m) with one of three microtopographic treatments (control, ridged, and hilled) (Figure 3-1b). Only the hilled treatment on the south-facing slope was utilized in this study. For more details on the research site and treatment setups, please see chapter 2 of this thesis.

Salvaged upland forest floor material (FFM) and lowland peat mineral mix (PMM) were used as coversoils for the overburden structure. The FFM material is composed of a mixture of the L, F, H organic horizons, and the A and B mineral horizons from Brunisolic soils salvaged to a depth of approximately 30 cm. This material was sourced from upland sites dominated by jack pine that had shallow organic LFH horizons, which were approximately 5 cm thick. The lowland peat mineral mix (PMM) was salvaged to a depth of 3 m from lowland soils that are dominated by an organic soil layer which can vary depth and the proportion of mineral and peat components. Both surface soils were stock piled for only a short period (< 3 months) until being placed in fall 2014 using D6 Caterpillar® bulldozers. The overburden structure was leveled, and site restoration began by applying a 35 cm layer of PMM in the summer of 2014. Hills in this treatment were constructed in the winter when the surface (35 cm PMM) layer was frozen. Forest floor and PMM materials were randomly chosen and pushed downhill from the upper slope position using bulldozers and left as unconsolidated piles. Hills were placed in off-set rows approximately 1.5 m apart and measured approximately 3.5 m wide by 5 m long and 1.5 m tall (Figure 3-2).

Prior to tree planting in May of 2015, different planting microsite positions were identified on the created hills (Figure 3-3a). The selected microsite planting positions differed in both hill micro-aspect and hill micro-elevation, including toe and mid-slope positions in each micro-aspect, and the hill's crest. Three tree seedlings were planted at the toe and mid-slope micro-elevations in each micro-aspect of the hill (Figure 3-3a and b) with an additional three seedlings planted at the crest position, for a total 27 seedlings on each hill. Planting stock was nursery produced 1-year old seedlings of either trembling aspen, white spruce or jack pine grown from open pollinated seed sources local to the area (Table 3-1). A replicate hill at the upper and lower slope positions (defined as the upper and lower 30 m of the slope) for both hill substrate materials (FFM and PMM) was planted in each block. In total, seedling growth characteristics were measured on 12 hills (2 substrates × 3 species × 2 positions) within each block (Figure 3-3c). Preliminary analysis showed that seedling growth characteristics (height and RCD) did not significantly differ between the slope positions and there were no significant block interaction terms. Since the hills were approximately 75 m apart, the hills at the different slope positions were considered independent replicates (n=10).

3.2.3 Sampling

Field measurements

To assess the influence of microsite position and substrate type on the early growth of planted aspen, jack pine and white spruce seedlings, height and root collar diameter (RCD) measurements were taken after planting and then again in August 2017 (after three growing seasons) and compared among the different microsite positions. Competition for resources among the recently planted seedlings was considered low this early on in establishment which allows for meaningful growth comparisons. Data collected from the hills was used to analyze growth responses of trees at the microsite scale and compare growth between FFM and PMM cover soil types.

Biomass data was only collected from aspen in order to explore growth allocation in response to microsite conditions in greater detail. A total of one-hundred trembling aspen seedlings were destructively harvested from the PMM and FFM hills during the summer of 2017. Aspen was selected as the target species for this assessment as it is a faster growing species and it was assumed that aspen would respond quickly to differences in microsite conditions compared to the slower growing conifers, particularly in relation to root system development. One representative aspen seedling was harvested from 5 microsite positions found on each hill (i.e. toe, mid-slope and crest positions from the north and south micro-aspects) on both FFM and PMM hills, at upper and lower slope positions in the five blocks (n = 10) (Figure 3-3d). When selecting representative seedlings for harvest, the approximately average-sized aspen seedling was selected from each microsite position based on height. The root system of each selected seedling was fully excavated, focusing on the main lateral roots extending from the root plug. To describe the architecture of the root system in more detail, root length and their general growth directions were recorded. Three general growth directions of lateral surface roots were identified as growing uphill, downhill, or laterally (i.e. parallel to the hill contour). Roots were cut, separated and bagged based on their growth direction. All samples were transferred to freezers for storage at -20 °C on the same day of excavation to preserve the samples before laboratory measurements.

3.2.4 Laboratory measurements

Seedling samples were separated into root, stem and foliage tissues. Roots were carefully washed, and all tissue samples were oven dried at 70 °C for 3-4 days, or until a consistent weight was achieved, and were then weighed to measure dry mass. Tissue dry masses were used to calculate different mass ratios to determine whether seedlings allocated resources to different organs, and whether roots system architecture changed as a result of microsite planting position. The following mass ratios were calculated: shoot mass ratio (SMR, total shoot mass over total seedling mass), leaf mass ratio (LMR, total foliar mass to total seedling mass), root mass ratio (RMR, total root mass over total seedling mass), root to shoot ratio (RSR, total root mass over total shoot mass), and root to leaf mass ratio (RLR, total root mass over total leaf mass). Total root system length was calculated by averaging the length of all roots found on a harvested aspen seedling, which was then used to compare root system architecture between planting microsites. Ratios of lateral root mass based on growth direction were also compared by calculating the uphill, downhill and lateral root masses relative to the total root mass that extended from the original root plug.

3.2.5 Statistical analysis

All statistical analyses were executed in R Software (v 3.4.3, R Core Team 2018). Prior to analysis, datasets were tested to ensure that assumptions of normality and homogeneity of variances were not violated for analysis of variance (ANOVA) tests, and appropriate transformations were made to meet those assumptions when necessary. Effects were considered significant at $\alpha = 0.05$; post-hoc least-squares means were compared using Fisher's LSD test with Holm's method for p-value adjustment for significant main effects and interactions.

Statistical assessment of tree height and RCD to microsite position and hill substrate type

Final height and RCD measurements from August 2017 were compared using three-way ANOVAs to evaluate the influence of micro-elevation, hill material, and hill slope position on planted seedlings for each species. Hill slope position did not significantly influence height or RCD measurements, so the analysis was simplified to a two-way ANOVA using micro-elevation and hill material type as the fixed effects. The non-significant influence of hill slope position allowed samples at upper and lower slope positions to be considered separate replicates, increasing the number of replicates from 5 to 10 (see above). Micro-elevation responses were evaluated by averaging height or RCD from toe, mid-slope, and crest positions on hills. When data failed normality and homoscedasticity assumptions, it was manipulated using square root and $\log_{10}$ transformations prior to ANOVA testing. When significant interactions between fixed effects were present in the analysis a type III ANOVA was completed, and when no significant interactions were present the interaction was removed from the model and a type II ANOVA was completed.

The effects of micro-aspect, hill material type, and hill slope position on seedling height and RCD in 2017 were also compared using three-way ANOVAs. Hill slope position did not significantly influence height and RCD responses and was removed from the analysis. ANOVA testing was completed with a two-factor test using micro-aspect and hill material type as the fixed effects. Seedling response to planting micro-aspect was evaluated by averaging measurements from seedlings at mid-slope microsites in each aspect of the hill. Square root and log10 transformations were used to compensate for failed normality and homoscedasticity assumptions prior to ANOVA testing. When significant interactions between fixed effects were present a type III ANOVA was completed, and when no significant interactions were present the term was removed from the model, and a type II ANOVA was completed.

Relative height growth (*(final height – initial height) / initial height*) from 2015 to 2017 (three growing seasons) was calculated to compare the influence of microsite position and hill material type among the planted aspen, pine and spruce seedlings. To compare growth responses among species, relative height growth was analyzed using three-way ANOVAs with micro-elevation, hill material type and species, or micro-aspect, hill material type and species as the fixed treatment factors.

Statistical assessment of tree tissues and root growth to microsite position and hill substrate type

Analyses of biomass and biomass allocation in aspen by microsite position were completed by comparing dry mass and tissue mass ratios. Foliar, stem, root, and total masses were used as the response variable in two-way ANOVAs with micro-aspect and hill material type, or micro-elevation and hill material type as the fixed effects. Mass ratios were calculated and used to compare biomass allocation based on planting position and substrate type. Biomass allocation response variables include shoot mass to total mass, foliar mass to total mass, root to shoot mass, root to foliar mass, and root mass to total mass ratios. Two-way ANOVA testing was used to assess the ratio response compared to micro-elevation and hill material, or micro-aspect and hill material. Analysis of micro-aspect responses was completed with trees harvested from the mid micro-elevation only. When homoscedasticity assumptions were violated, models accounted for this by using weighted ANOVAs. Linear and linear mixed effect models from the *nlme* R package (Pinheiro et al. 2018) were used depending on the presence of a significant random block effect.

Root system length was analyzed using two-way ANOVAs with micro-elevation and hill material type or micro-aspect and hill material type as the fixed treatment effects. Root length was compared using a three-way ANOVA with root growth direction, micro-aspect, and hill material type as the fixed effects. In instances where no roots were found in a particular growth direction, a zero value was recorded. Lateral root mass proportion was analyzed using the glmmTMB function with a Beta family distribution for proportion data. To account for 0 and 1 values in the dataset, root mass proportion data was transformed to fit the Beta distribution following the methodology used in Smithson and Verkuilen (2006):

$$Transformed\ mass\ proportion = \frac{mass\ proportion * (number\ of\ samples - 1) + 0.5}{number\ of\ samples}$$

This transformation fit the data between zero and one, as required for analysis of data within a Beta family distribution. Model selection was based on AIC value comparisons from created glmmTMB models in R. In this instance, the selected model compared the response of lateral root mass proportion to growth direction and hill material type and had a random factor to account for between block variation.

3.3 Results

3.3.1 Seedling aboveground growth response to planting microsite and substrate type

The height and RCD of planted seedlings in 2017 was used to assess the growth responses of seedlings to planting microsite position and hill material type in the final year of measurement. Trembling aspen height was affected by micro-elevation; however, the response was dependent on the hill substrate (micro-elevation × hill material type interaction, $p < 0.01$; Table B-1) (Figure 3-4a). There was no difference in aspen seedling height at the toe position between the two material types; however, aspen seedling height decreased moving from the toe to crest micro-elevation on FFM hills (Toe: 127.7 cm, Mid: 91.6 cm, Crest: 79.5 cm), while seedling height was not different between the micro-elevations on PMM hills (Toe: 132.8 cm, Mid: 148.5 cm, Crest: 134.9 cm) (Figure 3-4a). Overall, aspen seedlings were taller and had greater RCD on PMM hills compared to the FFM hills (both $p < 0.001$, Figure 3-4). Root collar diameter of aspen responded similarly, where RCD decreased with increasing micro-elevation on FFM hills (Toe: 14.4 mm, Mid: 10.4 mm, Crest: 9.8 mm) but not on PMM hills (Toe: 14.5 mm, Mid: 15.8 mm, Crest: 15.9 mm) (micro-elevation × hill material type interaction, $p < 0.005$; Figure 3-4b). Trembling aspen height and RCD were not influenced by micro-aspect (Table 3-2; Table B-2). Height and RCD of jack pine and white spruce seedlings were similarly affected by micro-elevation and hill material type (both micro-elevation × hill material interaction, $p < 0.05$; Table B-1) (Figures 3-5a, b). Pine height and RCD were greatest at the toe position and decreased towards the crest micro-elevation on FFM hills (Height – Toe: 64.4 cm, Mid: 52.2 cm, Crest: 47.0 cm; RCD – Toe: 12.1 mm, Mid: 10.3 mm, Crest: 9.0 mm), while they did not differ between micro-elevations on PMM hills (Height – Toe: 71.6 cm, Mid: 76.2 cm, Crest: 74.7 cm; RCD – Toe: 12.8 mm, Mid: 14.6 mm, Crest: 15.2 mm). Jack pine height and RCD were not influenced by planting micro-aspect (Table 3-3; Table B-2). Height and RCD of white spruce seedlings in 2017 were also impacted by micro-elevation, and this response was dependent on hill material type (both micro-elevation × hill material interaction, $p < 0.05$). White spruce seedlings were taller at the toe position compared to the crest micro-elevation on FFM hills (Toe: 53.4 cm, Mid: 44.6 cm, Crest: 44.3 cm) and did not differ between micro-elevations on PMM hills (Toe: 61.3 cm, Mid: 64.9 cm, Crest: 62.1 cm) (Figure 3-6a). Seedlings were taller and had greater RCD at the mid and crest micro-elevations on PMM hills (RCD – Toe: 12.9 mm, Mid: 15.3 mm, Crest: 16.2 mm) compared to FFM hills (RCD – Toe: 12.1 mm, Mid: 10.9 mm, Crest: 11.5 mm) but did not differ between material types at the toe micro-elevation (Figure 3-6b). White spruce height and RCD were not affected by planting micro-aspect (Table 3-4; Table B-2).

When compared among species, relative height growth over the three growing seasons (RHG) was affected by micro-elevation, however this response varied by species ($p < 0.05$), where only aspen showed a response to micro-elevation (Toe: 2.4 cm/cm, Mid: 2.8 cm/cm, Crest: 2.1 cm/cm) while both conifers did not (Figure 3-7). Overall, the RHG of aspen was greater than that of pine (Toe: 1.0 cm/cm, Mid: 1.1 cm/cm, Crest: 0.89 cm/cm) and spruce (Toe: 0.7 cm/cm, Mid: 0.7 cm/cm, Crest: 0.6 cm/cm), while RGH of spruce and pine were not different from each other.

Relative height growth was also affected by micro-aspect, but this response was dependent on hill material type and the species (micro-aspect × hill material type × species interaction, $p < 0.05$). Aspen grew relatively more compared to the other species on the south aspect on FFM hills (4.2 cm/cm) (Figure 3-8), followed by the south aspect on PMM hills (3.5 cm/cm), and RHG was the least on the east aspect of FFM hills (2.2 cm/cm). Neither jack pine nor white spruce were affected by micro-aspect on FFM and PMM hills.

3.3.2 Aspen growth and biomass allocation response to planting position and substrate material

In contrast to the seedling averages (see above), the height and RCD of excavated trembling aspen seedlings were not different among the micro-elevations (Table B-3), micro-aspects (Table B-4), or hill material types, although an attempt was made to collect average sized seedlings for each position (Table 3-5 and 3-6). Excavated seedlings were not the truly average size of the seedlings available for harvest, so the addition of non-harvested seedling measurements altered the height and RCD measurements enough to show a growth response in statistical testing. Additionally, root mass, foliar mass, shoot mass, and total mass of harvested aspen were not affected by micro-elevation, micro-aspect, or hill material type (Table 3-5 and 3-6; Table B-5 and B-6). However, total root length of aspen was greater on PMM hills compared to FFM hills (ANOVA testing micro-elevation – PMM: 138.9 cm, FFM: 100.4 cm; ANOVA testing micro-aspect – PMM: 120.8 cm, FMM: 93.7 cm) (Figure 3-9; Table B-7 and B-8). Average root length was greater on south micro-aspects (98.9 cm) compared to north micro-aspects (78.0 cm) ($p < 0.05$; Table B-9) (Figure 3-10) but was not affected by hill material type or root growth direction.

There were no differences in dry mass allocation to the different tissue organs of harvested aspen seedlings as tissue mass ratios did not differ among micro-aspect (Table B-11), micro-elevation (Table B10), or hill material type and their interactions (Table 3-7 and 3-8). However, the proportion of shallow roots growing in different directions was significantly affected in seedlings growing on the hill slopes ($p < 0.001$; Table B-12). A greater proportion of the root system was represented by roots that grew up (0.45) or down (0.40) slope compared to roots that grew laterally (0.20) along the hill contour (Figure 3-11).

3.4 Discussion

Seedling aboveground growth in response to specific microsites was largely influenced by hill substrate material. All species planted at the mid and crest micro-elevations on PMM hills had greater height compared to those planted on FFM hills. This difference in growth can likely be attributed to the higher soil moisture availability in the PMM hills compared to the FFM hills, which were not monitored in this study, but are described in detail for the same site in Melnik et al. (2017). The high proportion of organic material contained within the PMM results in much greater water holding capacity (Walczak et al. 2002) which becomes more important on raised microsites such as the mid and crest positions on the hills. Soil moisture is a strong limiting factor in seedling establishment particularly in relatively dry climatic zones such as the eastern boreal mixedwood region of Alberta. As a result, micro-elevation affected the height of seedlings planted more strongly on the drier FFM hills, where seedlings grew taller at the toe position compared to the elevated positions. This is supported by the soil moisture data from Melnik et al. (2017) who observed a stark decreasing soil moisture gradient on FFM hills, with the greatest amount of soil moisture being at the toe microsite and the least at the hill's crest. Hills composed of PMM had greater soil moisture availability over the season and the soil moisture gradient among elevational positions was less severe (Melnik et al. 2017). The hypothesis that the growth responses appear to be mostly soil moisture driven is supported by the observation that seedling height and RCD on FFM hills at the toe position was not different from the toe position on PMM hills. This suggests that growing conditions are similar between the two hill material types when soil moisture is not limiting. A similar observation was made in another study where seedlings experienced decreased growth at the crest position of similarly sized loosely pilled hills used in a coal mine reclamation (Gilland and Mc Carthy 2012).

Interestingly, micro-aspect did not have a significant effect on early seedling growth; growth differences were expected due to the northern latitude of the site where sun angles play a significant role in energy input on soil surfaces. It is possible that the created hills were too small to create a large enough differences to sun and wind exposure, and moisture retention characteristics (Macdonald et al. 2015a). However, it was expected that these conditions would only be a significant driver early on in establishment as canopy closure would reduce the possible influence of micro-aspect. Future studies could explore the role of hill size and distribution on early plant establishment and growth.

When comparing among species, only aspen responded to microsite conditions as its relative growth (RHG) was greatest at the mid micro-elevation and on south facing micro-aspects of FFM hills. It is possible that this micro-elevation provided more ideal growing conditions, with an appropriate balance of energy input (warm soils) and soil moisture conditions compared to the crest and toe micro-elevations (Perala 1990, Landhäusser and Lieffers 2001, Heineman et al. 2010). Interestingly, this response was only seen in aspen growing on FFM hills, which may be related to aspen's ability to quickly grow extensive root systems, expanding roots into areas with higher moisture availability. In the PMM hills where soil moisture was adequate, other factors such as soil temperature (Landhäusser and Lieffers 1998) and soil nutrient availability could have played a role in the lack of response (Pinno et al. 2012).

It was further hypothesized that trembling aspen root growth would increase in microsite locations that receive greater sun exposure, such as mid-slope and crest micro-elevations, as supporting literature suggests that the root growth of aspen would increase with greater soil temperature (Heineman et al. 1999, King et al. 1999). However, the root growth responses of aspen to the growing conditions described above could not be substantiated further with detailed measurements of carbon growth allocation. Aspen seedlings did not differ in mass allocation among microsite planting positions. This is possibly related to the selection of seedlings for excavation (see results). As only a subset of seedlings were excavated, differences detected in the aboveground measurements were not observed in the harvested seedlings, which likely relates to the lower replication and/or failing to collect the appropriate seedling average to the treatment.

Root lateral growth proportion by root growth direction was not affected by micro-aspects of hills, similar to the aboveground growth responses of aspen in the 2017 growing season. Root lengths were not different between growth directions, while root mass proportions were greater for roots growing towards the crest and the toe compared to the lateral growth direction. These responses could be related to the need for stability of the tree on the sloped surface but could also be an indicator of increased resource acquisition in the upper and lower portions of the hill. To my knowledge, this is the first study exploring the rooting architecture of aspen during early establishment in response to microtopographical position. The results of this study are limited by the exploratory nature and methodology used to map roots. In the field, it was not feasible to quantify whether roots continued laterally as surface roots or went down vertically accessing resources from the center of the hill. Subsequently, root growth direction results and the mass attributed to it needs to be viewed with caution.

Successful establishment of seedlings planted on reclamation sites is impacted by the availability of microsites (Gilland and Mc Carthy 2012). The completion of this study has demonstrated the potential of substrate material and planting microsite on the growth responses of three species commonly used in boreal forest reclamation following mechanical site preparation. In this study, microsite planting position had a greater influence on tree seedling growth response in substrates that were more prone to resource limitations such as soil moisture. Additions of organic amendments to coversoils might help reduce these limitations, however on exposed sites the growth and establishment of seedlings is enhanced by providing a larger range of available microsites by utilizing different soil substrate types and materials in combination with increased microtopographical variation to encourage the establishment of natural regeneration and desirable tree species (Harper et al. 1965, Haeussler et al. 1999, Bradshaw 2000, Hawkins et al. 2006, Hough-Snee et al. 2011, Macdonald et al. 2015a, Melnik et al. 2017, Frouz et al. 2018, Landhäusser et al. 2019).

3.5 Tables

Table 3-1: Initial average height (cm) and root collar diameter (mm) of seedlings planted on FFM and PMM hills.

	Height	*Root collar diameter*
Trembling Aspen	26.89	2.26
Jack Pine	28.30	3.70
Spruce	27.97	3.93

Table 3-2: Average trembling aspen height (cm) and root collar diameter (mm) on the available planting micro-aspects and hill material types. No significant interactions exist between micro-aspect and hill material type. Letters represent statistical differences ($p < 0.05$, $n = 5$).

		Trembling Aspen	
		Height	*Root collar diameter*
Micro-aspect	East	120.318 a	12.861 B
	North	124.848 a	13.405 B
	South	135.174 a	15.463 B
	West	121.507 a	12.987 B
Hill Material	PMM	151.796 x	16.161 Z
	FFM	94.664 y	10.717 W

Table 3-3: Average jack pine height (cm) and root collar diameter (mm) on the available planting micro-aspects and hill material types. No significant interactions exist between micro-aspect and hill material type. Letters represent statistical differences ($p < 0.05$, $n = 5$).

		Jack Pine	
		Height	*Root collar diameter*
Micro-aspect	East	64.263 a	12.174 B
	North	62.209 a	12.143 B
	South	69.558 a	13.450 B
	West	62.571 a	12.174 B
Hill material	PMM	76.609 x	14.615 W
	FFM	52.395 y	10.309 Z

Table 3-4: Average white spruce height (cm) and root collar diameter (mm) on the available planting micro-aspects and hill material types. No significant interactions exist between micro-aspect and hill material type. Letters represent statistical differences ($p < 0.05$, $n = 5$).

		White Spruce	
		Height	*Root collar diameter*
Micro-aspect	East	54.059 a	13.194 B
	North	55.952 a	12.674 B
	South	54.486 a	13.690 B
	West	56.016 a	13.393 B
Hill material	PMM	64.789 x	15.304 W
	FFM	44.061 y	10.872 Z

Table 3-5: Average height (cm), root collar diameter (mm), foliar mass (g), shoot mass (g), root mass (g) and total mass (g) of trembling aspen across micro-elevations and hill material types. No statistically significant differences existed between micro-elevations or hill material types, and no significant interactions existed ($n = 10$).

		Height	RCD	Foliar Mass	Shoot Mass	Root Mass	Total Mass
Micro-elevation	Crest	94.732	11.784	20.110	35.010	24.773	79.892
	Mid	105.577	12.247	18.775	34.888	21.185	74.847
	Toe	102.746	12.052	19.782	35.905	25.819	81.507
Hill Material Type	FFM	99.691	11.480	15.974	27.993	19.180	63.147
	PMM	104.635	12.644	22.785	42.340	28.133	93.258

Table 3-6: Average height (cm), root collar diameter (mm), foliar mass (g), shoot mass (g), root mass (g) and total mass (g) of trembling aspen across micro-aspects and hill material types. No statistically significant differences existed between micro-aspects o or hill material types, and no significant interactions existed ($n = 10$).

		Height	RCD	Shoot Mass	Foliar Mass	Root Mass	Total Mass
Micro-Aspect	North	116.453	13.002	20.031	38.450	20.889	79.370
	South	95.245	11.492	17.519	31.325	21.481	70.324
Hill Material Type	FFM	102.958	11.571	16.746	30.630	20.152	67.528
	PMM	108.065	12.924	20.803	39.145	22.218	82.166

Table 3-7: Average trembling aspen tissue mass ratios across micro-elevations on FFM and PMM hills. No statistical differences or main effect interactions were found (n = 10).

		Shoot Mass Ratio	Foliar Mass Ratio	Root to Shoot Mass Ratio	Root to Foliar Mass Ratio	Root Mass Ratio
Micro-elevation	Crest	0.411	0.291	0.747	1.096	0.297
	Mid	0.445	0.282	0.659	1.078	0.273
	Toe	0.451	0.267	0.670	1.224	0.282
Hill Material	FFM	0.440	0.280	0.665	1.103	0.279
	PMM	0.440	0.276	0.698	1.173	0.283

Table 3-8: Average trembling aspen tissue mass ratios on north and south micro-aspects on FFM and PMM hills. No statistical differences or main effect interactions were found (n = 10).

		Shoot Mass Ratio	Foliar Mass Ratio	Root to Shoot Mass Ratio	Root to Foliar Mass Ratio	Root Mass Ratio
Micro-aspect	North	0.459	0.289	0.597	1.007	0.252
	South	0.430	0.275	0.722	1.148	0.295
Hill Material	FFM	0.469	0.302	0.571	0.923	0.229
	PMM	0.427	0.273	0.762	1.176	0.300

3.6 Figures

(a)

(b)

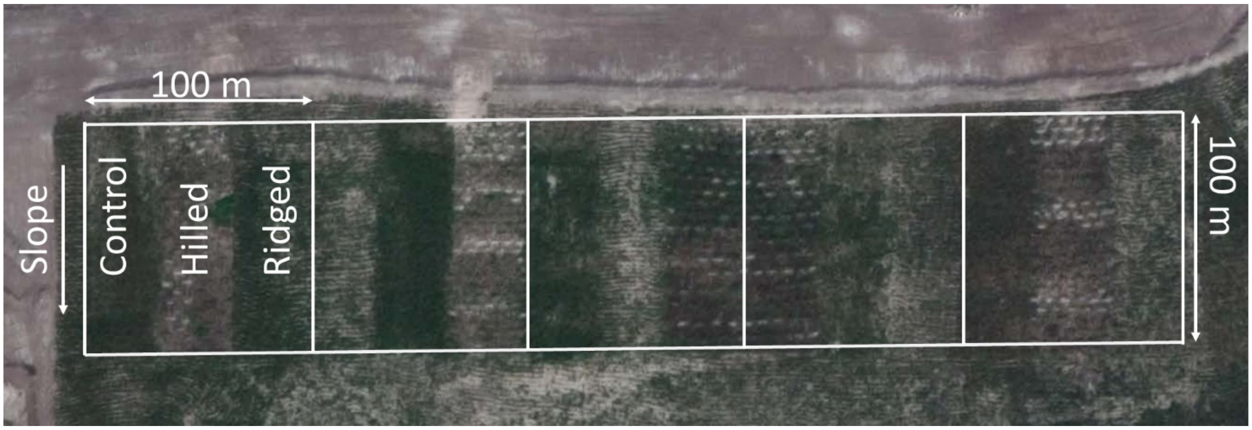

Figure 3.6-1: (a) Satellite view of the waste over burden dump with the study site outlined in red. (b) Satellite view of the five research blocks containing hills. The hills are part of a larger operational scale reclamation experiment.

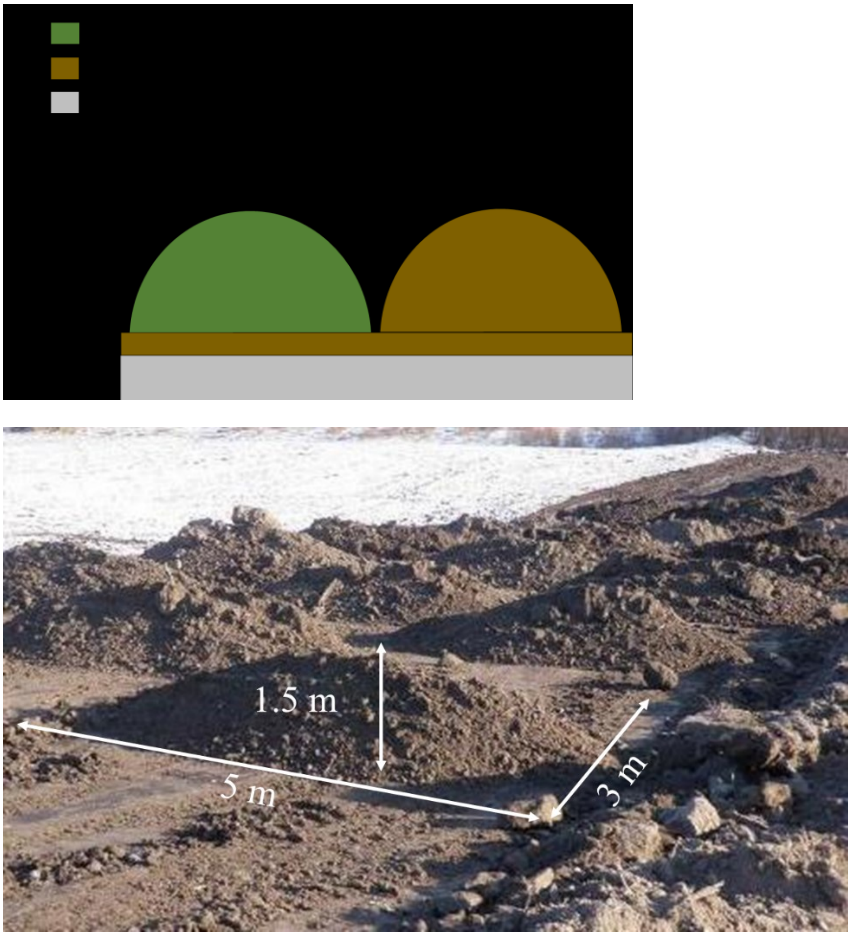

Figure 3.6-2: Material layering scheme of hills and hill dimensions following placement on the research slope.

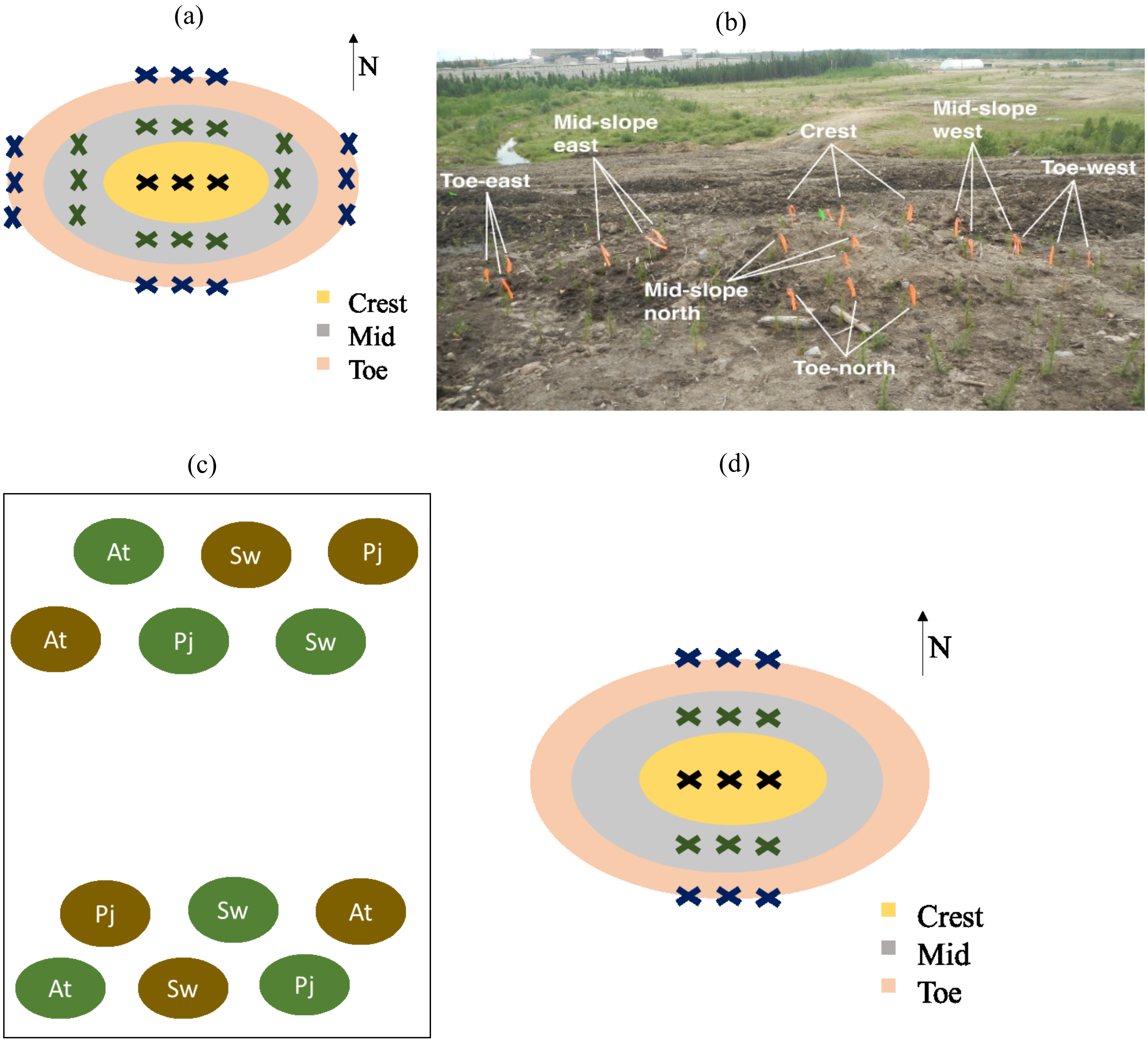

Figure 3.6-3: a) Description of planting microsites on FFM and PMM hills. b) Field example of planting microsite locations found on created hills. c) Distribution of hills selected for tree planting within each block. d) Planted seedlings available for destructive harvesting. One tree was selected at the crest position and one in the north and south micro-aspects at the mid and toe micro-elevations.

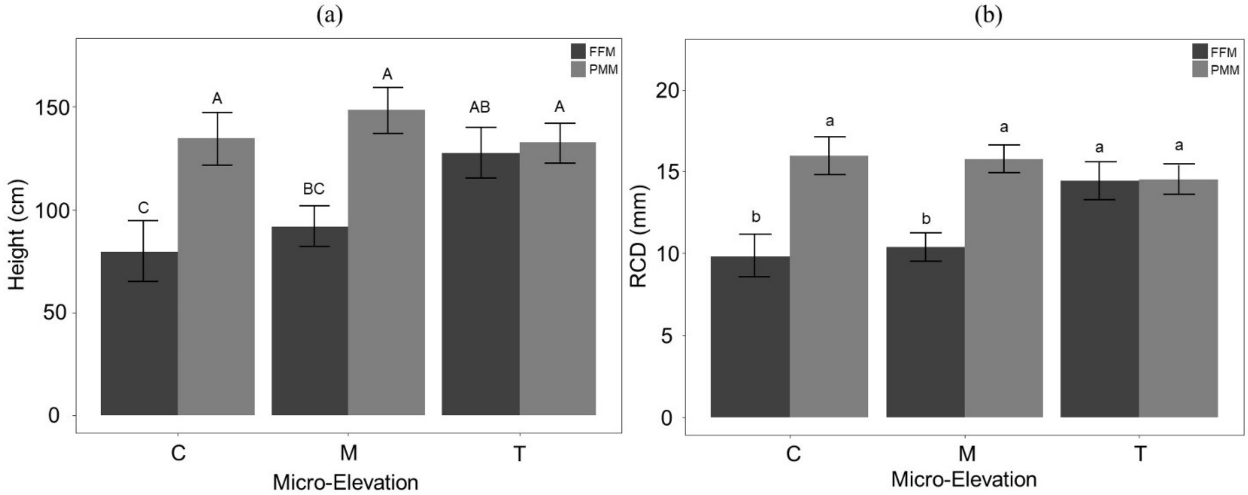

Figure 3.6-4: Trembling aspen height (a) and root collar diameter (RCD) (b) response to planting micro-elevation (C – crest, M – mid, and T – toe) on FFM and PMM hills in the 2017 growing season. A significant interaction exists between micro-elevation and hill material type (height $p < 0.01$, RCD $p < 0.005$). Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 10$), and error bars are standard errors.

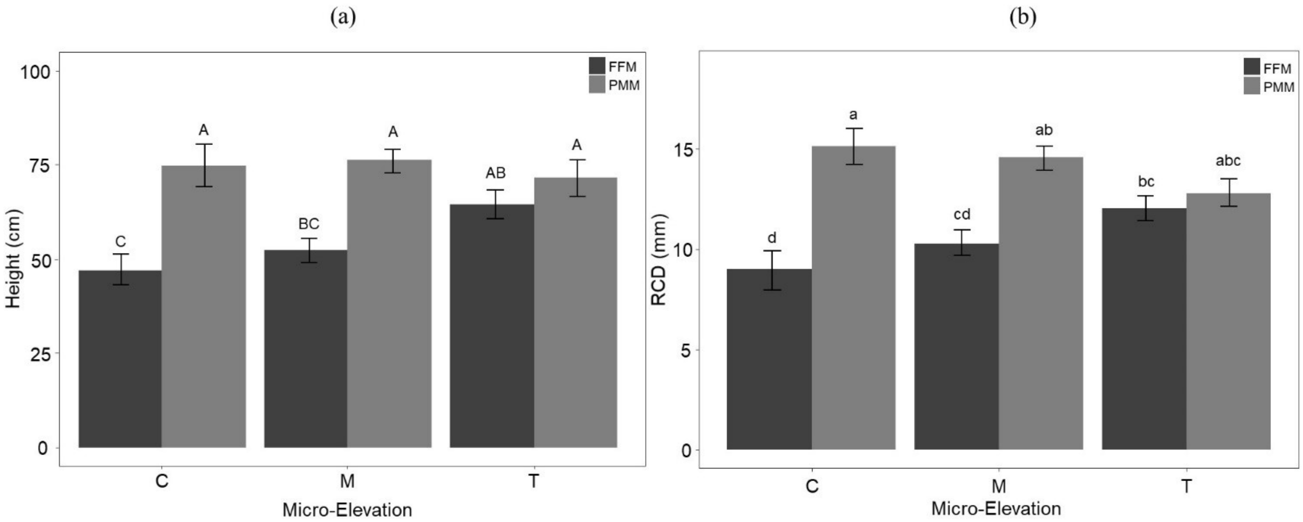

Figure 3.6-5: Jack pine height (a) and root collar diameter (RCD) (b) response to planting micro-elevation (C – crest, M – mid, and T – toe) on FFM and PMM hills in the 2017 growing season. A significant interaction exists between micro-elevation and hill material type (height $p < 0.05$, RCD $p < 0.001$). Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 10$), and error bars are standard errors.

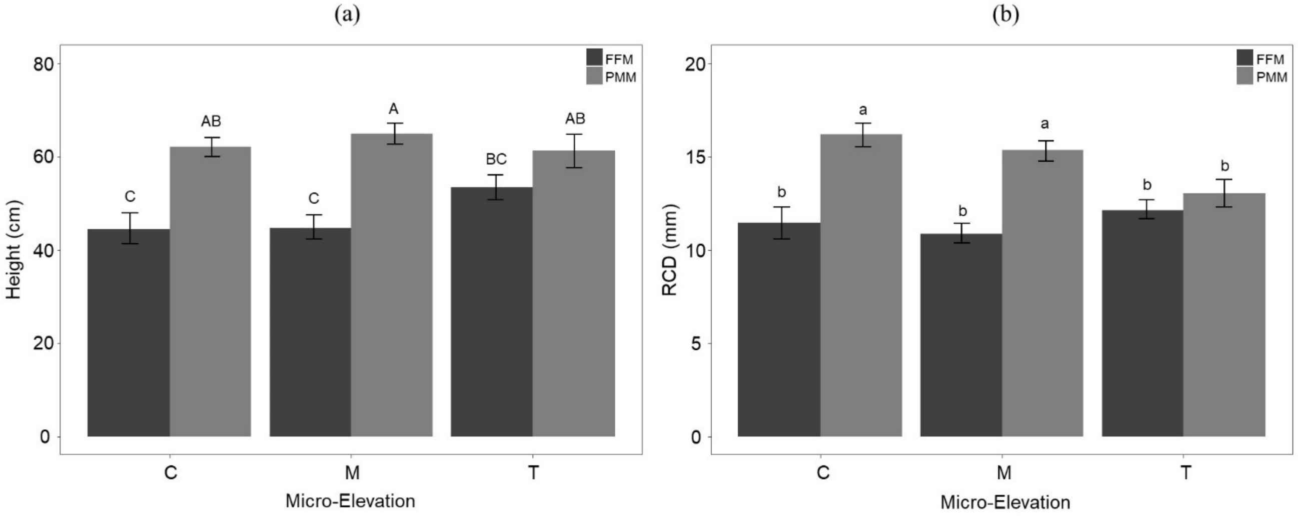

Figure 3.6-6: White spruce height (a) and root collar diameter (RCD) (b) response to planting micro-elevation (C – crest, M – mid, and T – toe) on FFM and PMM hills in the 2017 growing season. A significant interaction exists between micro-elevation and hill material type (height $p < 0.05$, RCD $p < 0.005$). Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 10$), and error bars are standard errors.

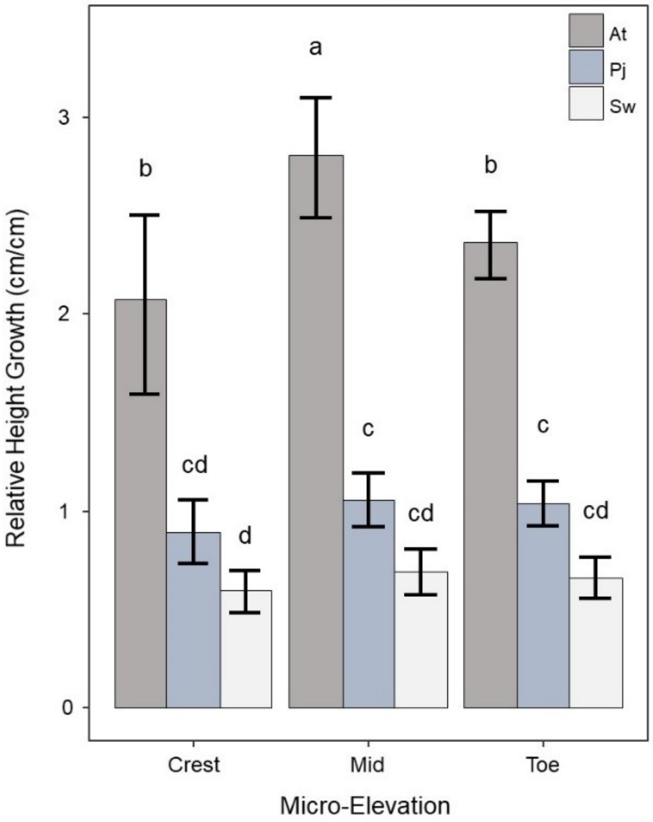

Figure 3.6-7: Relative height growth response of seedlings to planning micro-elevation. Seedling relative height growth responded differently based on micro-elevation and tree species (micro-elevation x species interaction, $p < 0.05$). Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 10$), and error bars are standard errors.

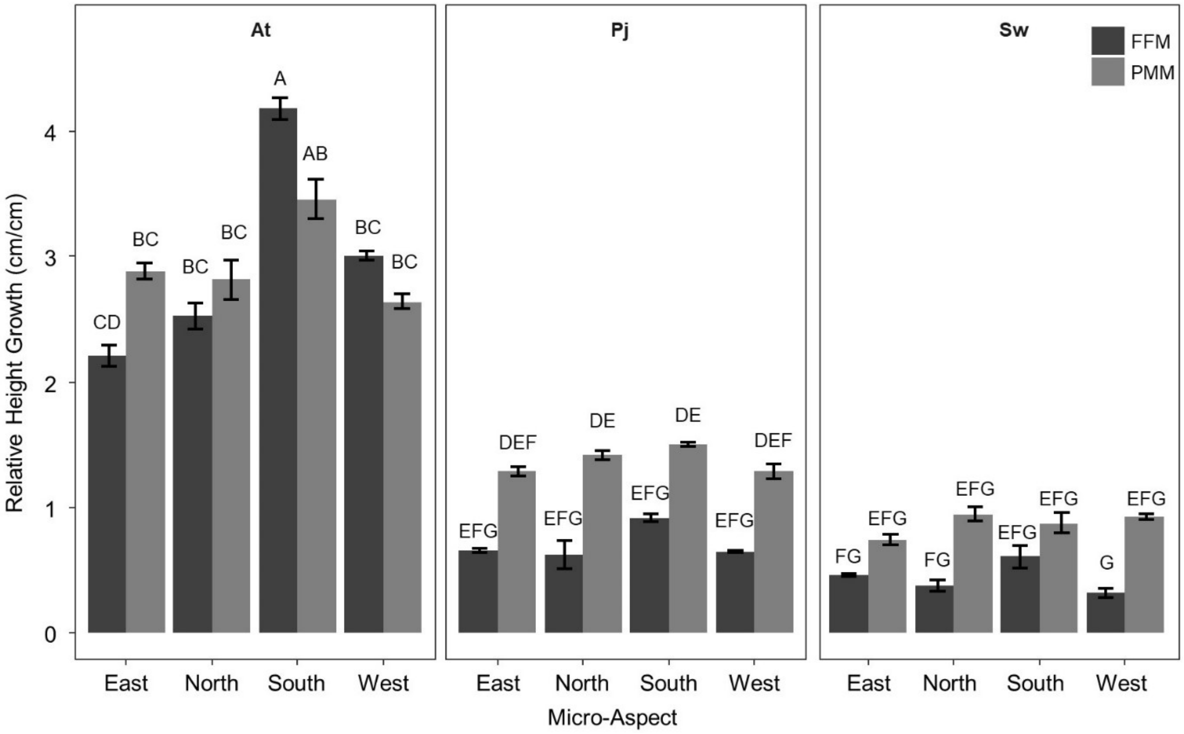

Figure 3.6-8: Relative height growth of seedlings planted across the different micro-aspects of hills. The relative height growth of seedlings was different depending on tree species, micro-aspect, and hill material type (species x micro-aspect x hill material type (species x micro-aspect x hill material type interaction, $p < 0.05$). Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 10$), and error bars are standard errors.

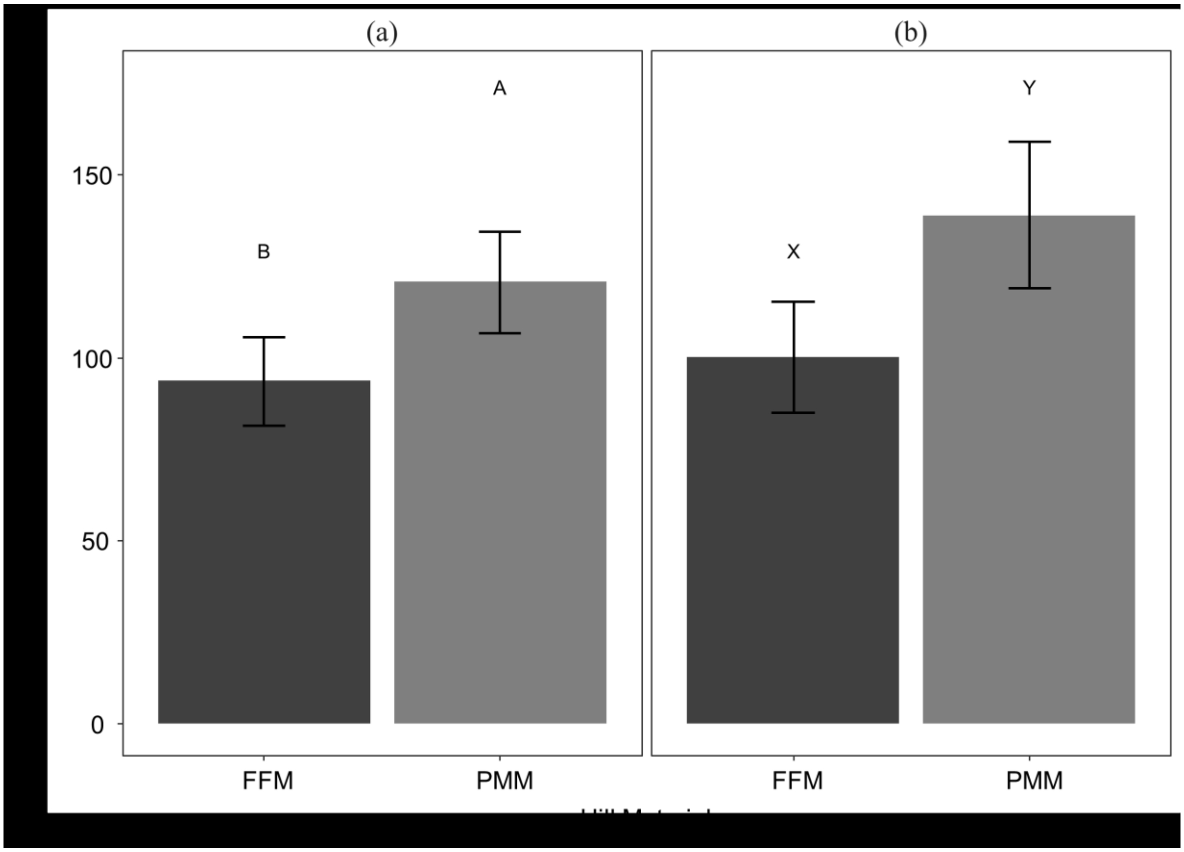

Figure 3.6-9: Average trembling aspen root system length by hill material type from analysis using (a) micro-aspect and hill material type, and (b) micro-elevation and hill material type. No significant interactions existed between hill material type and micro-elevation, or hill material type and micro-aspect. Differing letters represent statistically significant contrasts (α = 0.05, n = 10), and error bars are standard errors.

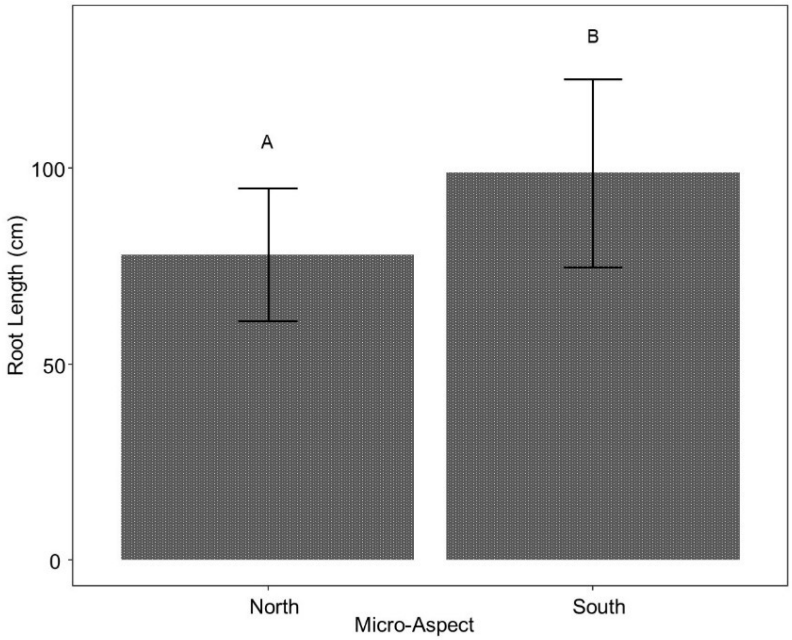

Figure 3.6-10: Trembling aspen root length across planting micro-aspects at the mid slope microsite. Statistical contrasts are from analysis using micro-aspect, root growth direction (uphill, downhill and lateral) and hill material type as the main effects. Root length was not affected by growth direction or hill material type, and no significant interactions existed between the main effects. Differing letters represent statistically significant contrasts (α = 0.05, n = 10), and error bars are standard errors.

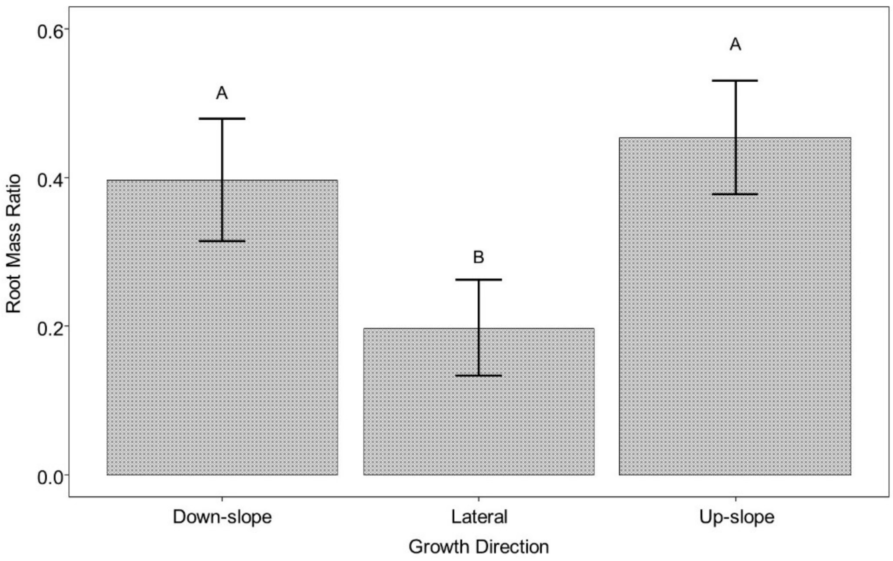

Figure 3.6-11: Lateral root mass proportion by growth direction of trembling aspen planted at the mid slope microsite for both north and south aspects on FFM and PMM hills. Root mass proportion was not affected by micro-aspect or hill material type, and no significant interactions existed between the main effects. Differing letters represent statistically significant contrasts ($\alpha = 0.05$, $n = 10$), and bars show standard errors.

Chapter 4: Synthesis and Discussion

4.1 Research Summary

This thesis aimed to assess the effects of microtopographic variation, specific microsite planting position, and cover soil substrate material on the growth and establishment of three upland boreal tree species planted on a surface mining reclamation site located in the Alberta oilsands region. To accomplish this goal, mechanical site preparation, a technique commonly utilized in forestry practices, was adapted to a mine reclamation site to create three different microtopographic treatments following coversoil placement: 1) control, 2) ridged and, 3) hilled. In the second chapter, an operational scale study was created to assess the growth and establishment of planted tree seedlings and the number of naturally regenerating trees and shrubs on the three coversoil microtopographic treatments created on two slopes of an overburden landscape feature. Transitioning to the microsite scale, Chapter 3 investigated the growth responses of seedlings planted at specific microsite positions found on the created hill structures and compared seedling growth responses between FFM and PMM coversoils. To further investigate growth responses to microsite position, trembling aspen seedlings were harvested to examine the morphological growth responses of above and belowground structures to microsite conditions.

Increasing coversoil microtopographic variation through different techniques of coversoil placement significantly influenced planted tree seedling growth. On the South site, trembling aspen height and RCD differed between treatments, where final measurements were greatest on the hilled treatment. Conifer heights did not differ between treatments, however average RCD was greatest in the hilled treatment for both jack pine and white spruce. On the East site, only jack pine height was influenced by microtopographic treatments, where average height was greatest on the ridged treatment. Aspen and white spruce height and RCD were not affected by treatments on the East site.

Utilizing the relative height growth of seedlings allowed for growth comparisons to be made among species. On the South site, species relative height growth (RHG) greatest in the hilled treatment. However, the level of response differed between species, where trembling aspen RHG was the greatest, and jack pine RHG was greater than spruce. On the East site, only trembling aspen RHG was influenced by microtopographic treatments, whereas jack pine and white spruce did not differ among treatments. Comparisons between species indicate that trembling aspen had greater RHG than jack pine and white spruce, while the conifer species did not differ from each other. Differences in relative height growth response among species is attributed to the different growth strategies of coniferous and deciduous trees. Improving microsite availability through the mechanical manipulation of coversoils has been shown to benefit the growth of planted tree seedlings on the South site in this study. Despite being much larger than hills formed in traditional mounding treatments used in forestry, hills created in this study were beneficial to the growth of planted tree seedlings, likely due to greater variability in soil edaphic conditions.

The recruitment of colonizing woody vegetation significantly increased with the addition of microtopography on both research sites. Particularly, aspen and willow regeneration was highly successful on both research sites, while few jack pine, white spruce, white birch and green alder were also found, likely due to limitations of seed dispersal. Increased regeneration is driven by seed capture and retention, and by the availability of microsite conditions capable of supporting seed germination. By increasing surface roughness, the hilled treatment was capable of providing sheltered areas from abiotic disturbance, allowing seeds to land and initiate germination. Additionally, the hilled treatment had the greatest range of available microsites, providing a variety of edaphic conditions that could meet the germination requirements of regenerating trees and shrubs. Conversely, little or no surface roughness and microsite variation on the control treatment did not shelter seeds from unfavourable conditions and offered more homogeneous microsite conditions which did not always meet seed germination requirements for regenerating trees. Seeds dispersed from nearby sources require adequate moisture for gemination, which is why regenerating individuals were commonly found at microsites with greater soil moisture, such as toe positions in the ridged and hilled treatments or on areas of exposed PMM soil. However, only tree regeneration was influenced by microtopographic variation, while the regeneration of willow had similar success on all treatments. At the landscape level, there was more regeneration from seed on the East site than on the South site, which can potentially be attributed the more moderate conditions on an east-facing slope in the northern hemisphere, compared to south facing slopes which receive greater amounts of solar radiation, potentially creating more stressful conditions.

In Chapter 3, the growth responses of planted seedlings were compared at different microsite positions (micro-aspect and micro-elevation) and material types on the created hills. Hill composition had a large influence on seedling growth response to microsite position. The growth of seedlings planted on FFM hills were significantly affected by planting micro-elevation, decreasing in height moving from the toe to crest micro-elevations. In contrast, the growth of seedlings planted on PMM hills were not affected by planting micro-elevation. When comparing growth responses of seedlings planted at the mid or crest micro-elevations, all species planted on hills composed of PMM grew taller than those planted on FFM hills. This is most likely related to the moisture holding capabilities of peat based coversoils, which are able to sustain greater soil moisture than upland sourced soils during dry conditions. This feature is especially important for raised microsites, such as the mid slope and crest positions created on hills in this study. The importance of moisture holding capacity of coversoils further is substantiated by the similar growth response of seedlings planted at the toe microsite position. All species grew similarly on PMM and FFM hills at the toe micro-elevation, where soil moisture content was the greatest compared to other microsite positions (Melnik et al. 2017). Planted seedlings were not influenced by planting micro-aspect, which is likely due to similar conditions existing between micro-aspects of created hills. When comparing relative height growth responses between species, the microsite scale study followed the results seen in Chapter 2, where aspen growth was greater than both jack pine and spruce, and conifer relative height growth did not differ from each other.

Of the measured aspen morphological structures, there were no significant differences in resource allocation to specific structural tissues when comparing aspen planted at different microsite positions, or on the two hill substrate types. Only the distribution of lateral root mass differed between root growth directions, which could be a response to resource allocation within the hill or to provide anchoring for trees planted on sloped positions. However, as methodologies used to map root growth are still developing, the results are limited as vertical changes in lateral root growth could not be captured.

4.2 Discussion and Future Research

Several studies have demonstrated that increasing site heterogeneity through the introduction of microtopographic variation can increase the growth of planted tree seedlings (Boateng et al. 2006, Fields-Johnson et al. 2014, Frouz et al. 2018, Lieffers et al. 2019). The formation of mounds or small hills to promote tree seedling growth is not a new concept, and has been utilized in traditional forestry settings for decades (Sutton 1991, 1993, Löf et al. 2006). This mechanical site preparation technique is usually introduced on sites where soil edaphic conditions are restrictive to tree seedling establishment and growth, such as sites which have low soil temperature or excess soil moisture, and is used to create planting microsites with more favourable growth conditions (Sutton 1993, Haeussler et al. 1999, Boateng et al. 2006, Evans et al. 2013). The hilled treatment in this study was inspired by mounding treatments used in forestry operations but was created at a much larger scale and did not form any pits or depressions. Maximizing the available range of microsite conditions by creating hills resulted in increased seedling height and RCD growth compared to the ridged and control treatments on the South research site. However, despite similar abiotic conditions existing on the South and East sites, these changes to seedling growth were not evident on the East site, suggesting an external factor which was not captured in this study may also be contributing to seedling growth differences. One such factor could be solar radiation or light exposure, as south-facing slopes receive more exposure than east and north aspect slopes in the northern-hemisphere. Levels of light exposure have been shown to significantly influence tree seedling growth and morphology (Logan 1965), and could be a contributing factor the results of this experiment.

Manipulating surface soil topography improved the recruitment of naturally regenerating trees and shrubs on both research slopes, and also increased the regeneration of understory species as similar results were found in a parallel study completed on this site (Melnik et al. 2017). The success of naturally regenerating woody species is a function of multiple factors, including the seed source, dispersal distance, climatic conditions during dispersal, and the availability of appropriate microsite conditions for seed germination which are not currently occupied by other competing vegetation (Primack and Miao 1992, Eastham and Jull 1999, Evans et al. 2013, Kokkonen et al. 2018, Landhäusser et al. 2019). Of particular interest, this study found that willow (*Salix* spp.) regeneration was less dependent on the availability of microtopography, while the regeneration of aspen was more prevalent on treatments with greater microtopographic variation. Willow regeneration was consistent throughout all treatments created in this study, likely due to less particular requirements for seed germination and a broader establishment niche, as willow often establishes on exposed mineral soils and microsites with adequate moisture and unobstructed sunlight (Porter 1990). Conversely, aspen regeneration was significantly greater with increased microtopographic variation and was greatest on the hilled treatment, suggesting that aspen regeneration from seed is dependent on the presence of microsite heterogeneity and sheltered areas associated with greater microtopography. Regeneration preference values for aspen and willow were greatest at sheltered toe microsite positions on the hilled and ridged treatments on both research sites. Our preference value results are similar to those found on post-harvest sites in natural systems, where Landhäusser et al. (2010) found that aspen regeneration was most common on sheltered concave microsites. Regenerating aspen and willow were also more commonly found on hills composed of PMM soil in the hilled treatment. This is likely related to the physical properties of PMM, as the increased water holding capacity of peat based soil is beneficial to the germination of aspen and willow seeds. Pinno and Errington (2015) also found that aspen regeneration was more prominent on PMM coversoil, and attributed this result to greater soil moisture and reduced competition levels experienced on PMM soil compared to FFM soil in their study. Relating these results to a forest restoration perspective, increasing coversoil surface microtopography is beneficial for recreating a forest canopy. The recruitment and successful establishment of overstory species, such as trees and shrubs, is an important factor for increasing habitat heterogeneity as shaded understory conditions begin to form (Frouz et al. 2018). Additionally, the promotion of overstory species establishment on the site offers faster successional pathways to climax forest conditions (Frouz et al. 2018), as the regeneration of overstory species is less likely to be inhibited by quick establishing species associated with disturbance.

The distribution of FFM and PMM coversoils throughout the created treatments is a potential factor contributing to differences of seedling growth and natural regeneration. Due to the methods of material layering during treatment construction, the hilled treatment had the greatest exposure of PMM soils. All treatments were created with an initial 35 cm base of PMM. The control and ridged treatments had an additional 15 cm layer of FFM material applied on top of the PMM, and microtopographic treatments were then created by manipulating this 50 cm coversoil cap. In contrast, the hilled treatment was created using the 35 cm PMM base, and hills were formed by loosely piling either FFM or PMM directly on top of the PMM base. The distribution of coversoils on the site influences soil moisture availability (Devito et al. 2012), thus influencing the germination of colonizing species and planted seedling growth. Soils which contain a greater proportion of soil organic matter, such as the PMM coversoil used in this study, have strong water retention characteristics, increasing soil moisture availability during periods of drought or reduced precipitation (Rezanezhad et al. 2016). It is possible that increasing the exposure of PMM soils combined with altered edaphic conditions on the hilled treatment created ideal conditions for seedling growth and seed germination.

The soil physical characteristics of the created treatments may also be affecting seedling growth and regeneration results as mechanical site preparation methods affected soil physical conditions. The control and ridged treatments were more mechanically intensive to create and had greater soil bulk density as a result of increased machine traffic, while the loose piling of soils and decreased machine traffic required to create the hilled treatment resulted in the lowest average soil bulk density (Melnik et al. 2017). As bulk density can significantly affect the establishment of planted seedlings and natural regeneration (Zenner et al. 2007, Fields-Johnson et al. 2014), the hilled treatment was the most capable of supporting seedling growth and establishment in this study.

Contrary to our initial hypothesis, growth responses of seedlings at the microsite scale followed very similar trends among species. On FFM hills, all species experienced greater height moving from the crest to the toe micro-elevations, while on PMM hills height remained consistent across micro-elevations. There was no significant height response to planting micro-aspect on either FFM or PMM hills for any of the study species. Growth differences between hill material types have been attributed to the greater water holding capacity of PMM soils, as soil moisture retention has been correlated with high soil organic matter content (Walczak et al. 2002). This theory is furthered by seedling response to micro-elevation position on FFM hills, where soil moisture content was inversely linked to hill elevation (Melnik et al. 2017). Seedling height and RCD measurements were not different between the toe micro-elevations on PMM and FFM hills, contributing to the hypothesis that seedling growth on hills in this study is largely driven by soil moisture.

Despite the literature which suggests that the morphological characteristics of seedlings could differ based on edaphic conditions existing at various microsite positions (Heineman et al. 1999, King et al. 1999), harvested aspen in this study only differed in it’s distribution of root mass. However, root architecture results related to growth direction and the distribution of seedling root mass were limited by the techniques used for measurement and data collection. It was not feasible to measure three dimensional root growth characteristics in a field setting. As such, our measurements were not able to capture changes in root depth over distances, and instead represent the approximate growth direction and root length in a two dimensional plane.

As this study was completed at an operational scale, there are benefits and limitations to the research completed. A primary benefit is that the results of this study indicate how increasing microtopographic variation of coversoils on reclamation sites can influence planted tree seedling growth and the ingress of colonizing woody vegetation. However, due to the operational nature of this study, research was limited to adhering to pre-existing site conditions and had to adapt to the daily operations occurring at the mine. For example, research was limited to two research sites, east and south facing, and could not be replicated on north or west aspect slopes, or on a non-sloping area. This study design was also limited to the availability of salvaged coversoils, meaning that treatments could not be created of just FFM or PMM soils, which could influence the seedling growth and regeneration results from Chapter 2. The size of microtopographic features was also restricted by the availability of machinery at the time of site construction. Topographic features could have been created at smaller or larger scales depending on the machinery used to form the microtopographic treatments. Evaluating the size and distribution of microtopographic features on the site could assist in maximizing planted seedling growth and the recruitment of woody vegetation. The physical characteristics of the created microtopographic treatments also introduces bias to the study, as the hilled treatment had significantly lower average soil bulk density than the other treatments (Melnik et al. 2017), which could be influencing seedling growth and woody species regeneration. To strengthen the results of this experiment, future research should recreate these microtopographic treatments with more consistent soil physical characteristics. Lastly, the development of a more in depth root growth study offers the opportunity to analyze the allocation of root resources based on microsite position and potentially the location of valuable resources on microtopographic features.

4.3 Management Implications

The results of this study have provided insight to and furthered the current understanding of utilizing microtopographic variation to benefit seedling growth and increase the natural regeneration of woody species on reclamation sites. This study suggests that seedling growth and natural regeneration on upland reclamation sites can be increased with the addition of surface soil microtopography to increase microsite heterogeneity. Additionally, the results of this study indicate that planting seedlings at specific microsites is particularly important on soils which have low water retention characteristics, as seedlings planted on FFM hills grew tallest at toe microsite positions where soil moisture was greatest (Melnik et al. 2017), but seedling growth did not differ between microsites on PMM hills. Furthermore, when selecting species for use on reclamation sites with microtopography treatments, moisture dependent species should be planted at toe positions of created features to improve establishment, while species adapted to well drained sites are best suited for crest microsite positions.

Incorporating microtopography through the formation of loosely piled hills not only offered benefits to planted seedlings and colonizing woody species, but the hilled treatment was operationally the fastest to create. As coversoils were loosely piled on top of the PMM base, less time was spent travelling across the site to smooth and distribute the recently applied coversoil material, reducing operational costs. The combination of forest restoration benefits and reduced operational costs makes creating loosely piled hills on top of an existing coversoil base an ideal treatment for upland reclamation sites.

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Appendices

Table A-1: Average height and RCD response to microsite position on the ridged treatment on the East and South sites. No statistical differences exist between microsites.

Slope	Microsite	Height (cm)	Root Collar Diameter (mm)
East	C	75.4	8.64
East	M	70.8	8.20
East	T	66.8	7.53
South	C	133.8	
South	M	126.8	
South	T	138.7	

Table B-1: Results of ANOVAs for seedlings planted across micro-elevations on created FFM and PMM hills. *P*-values show the effect of micro-elevation *(df=2)* and hill material type *(df=1)*. Significant interactions were found between micro-elevation and hill material type. Type III ANOVAs were completed due to the significant interactions. Bold values indicate statistical significance at α = 0.05.

Response Variable	Micro-Elevation (ME)	Hill Material (H)	Interaction (ME x H)
Aspen Height	**0.001**	**< 0.001**	**0.008**
Aspen RCD	**< 0.001**	**< 0.001**	**0.002**
Pine Height	**< 0.001**	**< 0.001**	**0.003**
Pine RCD	**0.004**	**< 0.001**	**< 0.001**
Spruce Height	**0.015**	**< 0.001**	**0.027**
Spruce RCD	0.278	**< 0.001**	**< 0.001**

Table B-2: Results of ANOVAs for seedlings planted across micro-aspects on created FFM and PMM hills. *P*-values show the effect of micro-aspect *(df=3)*, hill material type *(df=1)*. No significant interactions existed within the analyses, and type II ANOVAs were completed. Bold values indicate statistical significance at α = 0.05. Post-hoc comparisons of jack pine height on the different micro-aspects resulted in no significant differences despite the significant main effect.

Response Variable	Micro-Aspect	Hill Material
Aspen Height	0.899	**< 0.001**
Aspen RCD	0.349	**< 0.001**
Pine Height	**0.049**	**< 0.001**
Pine RCD	0.082	**< 0.001**
Spruce Height	0.999	**< 0.001**
Spruce RCD	0.479	**< 0.001**

Table B-3: Results of ANOVAs comparing height and root collar diameter (RCD) of harvested aspen seedlings on the different micro-elevations *(df=2)* and hill material types *(df=1)*. No significant interactions existed, and type II ANOVAs were completed. Bold values indicate statistical significance at α = 0.05.

Response	Micro-elevation	Hill Material
Height	0.4286	0.506
RCD	0.956	0.174

Table B-4: Results of ANOVAs comparing height and root collar diameter (RCD) of harvested aspen seedlings on the different micro-aspects *(df=1)* and hill material types *(df=1)*. No significant interactions existed, and type II ANOVAs were completed. Bold values indicate statistical significance at α = 0.05.

Response	Micro-Aspect	Hill Material
Height	0.076	0.696
RCD	0.289	0.341

Table B-5: Results of ANOVAs for aspen biomass across micro-elevations on created FFM and PMM hills. *P*-values show the effect of micro-aspect *(df=1)* and hill material type *(df=1)*. No significant interactions existed, and type II ANOVAs were completed. Bold values indicate statistical significance at α = 0.05.

Response Variable	Micro-Elevation	Hill Material
Root Mass	0.784	0.252
Foliar Mass	0.874	0.098
Shoot Mass	0.909	0.234
Total Mass	0.975	0.101

Table B-6: Results of ANOVAs for aspen biomass on the available micro-aspects on created FFM and PMM hills. *P*-values show the effect of micro-aspect *(df=1)* and hill material type *(df=1)*. No significant interactions existed, and type II ANOVAs were completed. Bold values indicate statistical significance at α = 0.05.

Response Variable	Micro-Aspect	Hill Material
Root Mass	0.988	0.697
Foliar Mass	0.526	0.308
Shoot Mass	0.389	0.403
Total Mass	0.463	0.369

Table B-7: Results for ANOVA testing of harvested aspen root system length on the different micro-elevations *(df=2)* and hill material type *(df=1)*. No significant interactions existed in the analysis, and a type II ANOVA was completed. Bold values indicate statistical significance at α = 0.05.

Response Variable	Micro-elevation	Hill Material
Root Length	0.0510	**< 0.001**

Table B-8: ANOVA results for harvested aspen root system length on the different micro-aspects *(df=1)* and hill material type *(df=1)*. No significant interaction existed in the analysis, and a type II ANOVA was completed. Bold values indicate statistical significance at α = 0.05.

Response Variable	Micro-Aspect	Hill Material
Root System Length	0.188	**0.030**

Table B-9: Results of ANOVA testing for harvested aspen root length response to growth direction *(df=2),* micro-aspect *(df=1)* and hill material type *(df=1)*. No significant interaction existed in the analysis, and a type II ANOVA was completed. Bold values indicate statistical significance at α = 0.05.

Response	Micro-Aspect	Hill Material	Growth Direction
Root Length	**0.039**	0.091	0.052

Table B-10: Results of ANOVAs for aspen biomass ratios on the different micro-elevations on created FFM and PMM hills. *P*-values show the effect of micro-elevation *(df=2)* and hill material type *(df=1)*. No significant interactions existed in the analyses, and type II ANOVAs were completed. Bold values indicate statistical significance at α = 0.05.

Response Variable	Micro-Elevation	Hill Material
Root Mass Ratio	0.568	0.980
Shoot Mass Ratio	0.141	0.950
Foliar Mass Ratio	0.433	0.944
Root Mass to Shoot Mass Ratio	0.464	0.627
Root Mass to Foliar Mass Ratio	0.638	0.931

Table B-11: Results of ANOVAs for aspen biomass ratios across micro-aspects on created FFM and PMM hills. *P*-values show the effect of micro-aspect *(df=1)*, hill material type *(df=1)*, and slope position *(df=1)*. No significant interactions existed in the analyses, and type II ANOVAs were completed. Bold values indicate statistical significance at α = 0.05.

Response Variable	Micro-Aspect	Hill Material
Root Mass Ratio	0.211	0.795
Shoot Mass Ratio	0.245	0.797
Foliar Mass Ratio	0.514	0.606
Root Mass to Shoot Mass Ratio	0.332	0.788
Root Mass to Foliar Mass Ratio	0.479	0.825

Table B-12: Chi-squared test results for root growth proportion across growth direction *(df=2)* and hill material type *(df=1)*. The model to analyze root growth proportion was selected based on AIC values and included root growth direction and hill material type as the fixed effects. No significant interactions existed in the analysis. Bold values indicate statistical significance at α = 0.05.

Response Variable	Growth Direction	Hill Material
Root Mass Proportion	**<0.001**	0.933