Local controls on tree seedling growth following mounding on peatland seismic lines in Brazeau County and Lac La Biche, Alberta

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Seismic lines in boreal peatlands are struggling to restore native canopy level vegetation. Mounding is a common restoration method that provides an advantageous growing environment for native tree seedlings. Although many mounding methodologies exist, it remains unclear how each unique mound type changes microsite conditions and influences seedling growth. This study compares five unique mounding and/or planting methods, and the influence of fertilization on black spruce and tamarack seedlings two years post-planting. This study was conducted the summer of 2021 in Alberta and observed seedling, mound microsite and seismic line variables for over 1500 samples. Data compared between mounding methods using ANOVA and characteristics supporting seedling growth were isolated using linear mixed effects models. The results of this study suggest that planted tree seedling survival and growth is heavily correlated with seismic line width, mound height, mound soil moisture and the diversity and density of surrounding vegetation. Comparing between mounding treatments, results indicate that traditional or 'Inverse' mounds are affected by heavy soil subsidence and have higher soil moisture content than any other treatment; they do not provide ideal habitat for black spruce seedlings. Non-traditional mounds like, Rip and Lift, Hummock Transfer and Inline, each had favourable microsite characteristics and support seedling growth. Regardless, Unmounded planting is a viable restoration technique if the seismic line has appropriate microtopographical variability and planting is targeted on the highest microsites. Tamarack seedlings had higher rates of growth than black spruce, but both species benefitted from fertilization with slow-release NPK (nitrogen-phosphorus-potassium) prills. Fertilizer was effective on all mounding treatments except Rip and Lift. The differences in seedling growth and ideal microsite characteristics identified in this study can be used to inform restoration planning. An effective landscape restoration plan can be tailored to existing seismic line characteristics and can build ideal mound microsites to support tree growth and the regrowth of forest canopies.

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Chapter 1: Literature Review

1.1 Introduction

Peatlands are important ecosystems that should be considered an asset to Alberta's landscapes. These ecosystems cover only 3% of the Earth but account for 12% of Canada and around 50% of Northern Alberta (Vitt, 1994). With this small global coverage, peatlands are calculated to store over 30% of global soil carbon stocks, providing a carbon capture benefit ten times their size (Rydin & Jeglum, 2013). As a sub-classification of peatlands, boreal peatlands are characterized by their waterlogged hydrology, vegetation composition of bryophytes and coniferous trees, and habitat for migratory birds and large boreal species (Holmgren et al., 2015). As a type of wetland, peatlands have a higher water table than other ecosystem types that creates a consistently wet landscape and provides ecosystem services like water quality filtration of pollutants and water quantity storage during flood events (Walbridge, 1993). Boreal peatlands also hold societal and cultural value, especially to First Nations communities with a long history of forest management (McGregor, 2011). To First Nations communities, this historic land is a source of food, a stronghold of cultural identity, and the baseline for the survival of future generations (McGregor, 2011). The effective management and restoration of these lands is of great interest to regional First Nations communities and their traditional forest knowledge and governance will benefit future restoration planning (Zurba, Diduck & Sinclair, 2016).

Today, Alberta's peatlands have a high level of human disturbance that reduces their connectivity as an ecosystem and their resiliency to new disturbances (Stevenson, Filicetti & Nielsen, 2019). The most common causes of human disturbance are related to the oil and gas industry, which includes the creation of seismic lines (Echiverri, 2021). Seismic lines are narrow linear features created during oil and gas seismic surveys. To perform these surveys, heavy equipment is transported across the landscape, causing large disruptions in peatlands as they remove mature canopy vegetation and compress peatland soils (van Rensen et al. 2015). Native trees are the last vegetation group to grow back after seismic line disturbance, with some seismic lines remaining deforested 50 years post-disturbance (van Rensen et al. 2015). The slow recovery of trees on seismic lines is often attributed to the wetter soils and reduced microtopography created during oil and gas activities (Stevenson et al., 2019). The deforestation of seismic lines in boreal peatlands is an issue since it breaks the connectivity of the canopy layer, which reduces forest connectivity, lowers total biodiversity, and interrupts the normal ecological functions and behaviour of native wildlife (Latham et al., 2013). In undisturbed peatlands, coniferous trees are often found growing on hummocks, which are drier, elevated areas that form naturally over a period of many years (Lovitt et al., 2019). Since natural hummocks are flattened on seismic lines, a working hypothesis in the field of peatland restoration is that tree regeneration can be supported by planting tree seedlings on built mounds that mimic hummocks (Von der Gonna, 1992). Mounding is a common practice in agriculture but is relatively new to forest ecosystem management (Davidson et al., 2020; Sutton, 1993). There are many different types of mounds, each with their own unique methodology and physical characteristics. While there is much we do not know about the effects of mounding on tree regeneration, studies from the past 10 years have shown that all types of mounds are generally beneficial to tree establishment and growth in boreal peatlands (Filicetti, Cody & Nielsen, 2019). However, there are also known detriments to using mounds as a method of restoration as they introduce a new form of disturbance to the ecosystem and can affect peatland ecosystem services (Smolander & Heiskanen, 2007). It is important to understand the specific benefits and detriments to using each kind of mound on boreal peatland seismic lines. The goal of this research project is to identify the characteristics of four unique mounding methods and study their effects on planted tree establishment and growth. With this knowledge, we can inform restoration planning initiatives to maximize tree restoration efforts while minimizing further disturbance to the ecosystem.

To paraphrase, Wolken et al. (2011) said it well: peatland trees are intertwined in many complex ecosystem relationships, and the strength and role of these relationships are still not fully understood. What is better understood is how trees affect their surrounding microsites. Trees are known to alter peatland hydrology as they increase the rate of interception and absorb soil water from a greater depth than other plant species (Holmgren et al., 2015). They also make up the uppermost canopy layer in peatlands which shades the landscape and alters the microclimate and range of species diversity (Holmgren et al., 2015). Together, these microclimatic conditions can create a positive feedback loop that favours the establishment of new tree seedlings (Eppinga et al. 2009). If this feedback loop is disrupted by removing existing trees, this will hinder the regeneration of boreal peatland trees. Overall, the ecosystem services of boreal peatlands are valuable and require conservation and restoration. Alberta's peatlands are currently at risk from human disturbances that decrease the rate of carbon capture and storage, decrease the integrity of the ecosystem, and enable competitive invasive species to enter the ecosystem (James & Stuart-Smith, 2000).

1.2 Vegetation Gradients and Drivers of Tree Growth in Peatlands

One of the unique and defining features of peatlands is their hummock-hollow surface topography. Hummocks are drier, elevated places in the peatland whereas hollows are at a lower elevation and are closer to the water table. The flatter regions in between hummocks and hollows are commonly called lawns and generally act as a transition zone with a blend of hummock and hollow characteristics (Nungesser, 2003). Hummocks are formed over a long period of time through a positive feedback loop between moss species diversity and acrotelm (the surface, low porosity layer of peat) formation (Belyea & Clymo, 2001). The most common bryophytes found in boreal peatlands are *Sphagnum* spp mosses, brown mosses and feather mosses, which form a moss carpet dominating the ground layer (Thiffault et al., 2013). Different species of moss accumulate peat at differing rates and this species diversity starts to change the rate of acrotelm development within peatlands (Nungesser, 2003). As the acrotelm grows thicker, it forms hummocks and provides a drier space for roots of vascular plants (Belyea & Clymo, 2001). The moss species that prefer to grow in drier conditions are often those that accumulate peat at a faster rate (Nungesser, 2003). As a result, a positive feedback loop is established where faster growing mosses dominate hummocks and continue to develop the acrotelm. Eventually, tall hummocks will reach a steady state of growth and see a decline in their rate of peat formation (Belyea & Clymo, 2001). Mosses that accumulate peat at a moderately-fast pace often form the lawns seen in peatlands whereas slow-growing mosses are more prevalent in the less developed hollows and prefer wetter soil conditions (Nungesser, 2003).

Similar to how moss species prefer different soil conditions and moisture contents, different vascular plant species have growing preferences across the peatland microtopography. Softwood trees like jack pine (*Pinus banksiana*), black spruce (*Picea mariana*), tamarack (*Larix laricina*) and balsam fir (*Abies balsamea*) are the most prevalent conifers in boreal peatlands and support the uppermost canopy, while Ericaceous shrubs dominate the understory layer (Lafleur et al., 2011). These types of woody vegetation are more commonly found growing on hummocks than on lawns or hollows as they prefer drier soil conditions (Caners et al. 2019). Ericaceous shrubs may compete with young conifer seedlings for nutrients and light as they occupy similar microsites in peatlands (Hébert et al., 2010). The risk of intraspecies competition is highest directly after a large disturbance like forest fires in boreal peatlands or the initial construction of the seismic line (Renard et al., 2016).

Bryophytes play a mutualistic role with trees by regulating hummock formation and providing access to water. For example, Pace et al. (2016) and Lett et al. (2020) examined inter-species competition and mutual interactions that suggest the moss carpet of peatlands is essential to tree recovery. This relationship further illustrates the importance of having an established vegetative layer to support tree seedling growth. Currently, there is discussion surrounding the ideal moss type to support tree regeneration since the complex interactions between vegetation communities are still not well understood (Pace et al., 2018; Lett et al., 2020). It is well known that the moss layer of a peatland is essential for its ecosystem integrity and function (Cornelissen et al. 2007). However, there is a precedent case that suggests bryophytes may have a competitive relationship with coniferous seedlings. Sphagnum moss carpets naturally reduce nutrient availability at the microsite level, and this may negatively affect trees if they cannot successfully increase their below-ground biomass to reach a wider area for soil nutrients (Malmer et al., 2003).

1.3 Role of Soils, Nutrients and Ectomycorrhiza on Tree Growth

Successful tree growth in boreal peatlands is also directly related to soil nutrient availability and physical soil conditions. Davidson et al. (2020) states that soil conditions are the limiting factor to boreal peatland tree establishment. Peatlands have unique soil structures and properties, and it is proposed that any changes to these soils will severely limit tree regeneration (Davidson et al., 2020). However, it is acknowledged that the link between soil properties and tree growth in boreal treed peatlands is not fully understood (Davidson et al., 2020). Firstly, we know that the moss layer affects the nutrient cycling of peatlands as moss carpets generally have low concentrations of available nutrients, which decreases the support to tree growth (Pace et al., 2018). For example, Pace et al. (2018) states that Sphagnum provides less available nutrients than feather mosses, but Lavoie et al. (2018) contradicts this statement. Mosses also regulate soil temperatures and reduce the variability in temperature change, creating a more stable environment for new tree seedlings (Lett et al., 2020). Finally, mosses positively impact the below-ground rooting processes associated with tree growth, although these processes are not well studied in a field environment (Shao et al., 2022). There is still much to learn about peatland soils and their relationship to tree regeneration. Overall, the impacts of climate change to peat soil function and nutrient cycling in peatlands is another key area of study that may impact the successful establishment of native tree species (Allison & Treseder, 2011; Mäkipää et al., 2023).

Fungal activity within the soil is also a key area of research in boreal peatlands. Ectomycorrhizal (ECM) associations are known to promote tree growth and a diverse and abundant population of ECM will further benefit tree seedling establishment (Mäkipää et al., 2023). Furthermore, increases in ECM biomass are linked to increases in soil organic carbon, thereby supporting peatland carbon sequestration (Mäkipää et al., 2023). Fungal associations can also be affected by the surrounding vegetation communities around coniferous trees. Moss composition can alter soil properties like pH and the oxygenation of the soil, which in turn impacts microbial mycorrhizal communities and fine rooting structure of growing trees (Kalliokoski et al. 2010). The benefits of mycorrhiza can also be reduced due to competitive pressures from Ericaceous shrubs who have been found to negatively impact the mycorrhizal symbiosis with conifer tree species (Dabros, Higgins, Santala & Aubin, 2022).

In a similar context, fertilization studies of peatlands have shown that N-rich fertilizers cause a decrease in ECM abundance but that wood ash fertilizers will increase ECM diversity and do not significantly affect abundance (Mäkipää et al., 2023). Fertilizer affects surface vegetation like moss, which has been observed to multiply in above-ground biomass when ash fertilizers are used in peatlands (Huotari, Tillman-Sutela & Kubin, 2009). However, the consistent application of high-N fertilizer has been known to produce a negative effect on Sphagnum moss and may limit their capability to sequester carbon effectively. Fertilizer is also known to positively affect coniferous tree species (Ernfors et al., 2010). There is often a scarcity of phosphorus and potassium in boreal peatlands that can act as a limiting agent in tree growth (Silfverberg & Moilanen, 2008). Using a PK fertilizer to introduce a greater amount of these nutrients, has proven to significantly increase the above-ground biomass of coniferous trees (Silfverberg & Moilanen, 2008). Although, it was determined that while a single application of P, improved P quantities in needles after three decades, K levels would decline within a few years and required consistent reapplication of fertilizer to retain ideal K nutrient levels

(Silfverberg & Moilanen, 2008). This reapplication is not advised as the continual application of fertilizer is known to have detrimental effects on the available carbon stocks in peatlands and can cause large disruptions in peatland nutrient cycling processes (Ojanen et al., 2019). Therefore, changes to boreal peatland soil nutrients through the use of fertilizer, fertilizer type and application counts are an important consideration in tree planting activities.

1.4 Seismic Lines

In Alberta, the most common disturbance to boreal peatland trees are oil and gas exploration activities such as seismic lines and well pads (Echiverri, 2021). Over the past 200 years, these individual oil exploration activities have accumulated to form an extensive pattern of environmental disturbance (Stevenson, Filicetti & Nielsen, 2019). To expand Alberta's growing oil industry in response to the global oil demand, seismic lines are used to identify new oil and natural gas deposits (Stevenson, Filicetti & Nielsen, 2019). Seismic lines are linear sections of cleared forest. Heavy machinery is used to clear lines by removing all trees and tall shrubs to map out bitumen deposit presence and depth using seismic waves and vibrations (Filicetti & Nielsen, 2020). Today, hundreds of thousands of kilometres of seismic lines persist across Alberta's forests and peatlands as most of these new and historic human disturbances have not recovered or reintegrated into the greater ecosystem (Dabros et al. 2017). Currently, some 50-year-old seismic line sites have not seen a successful regeneration of tree species, and it has been suggested that at least one third of unrestored seismic lines will fail to see any tree regeneration for at least another 50 years (van Rensen et al. 2015). These unrestored seismic lines are often the wettest, which leads to the conclusion that a wet landscape is the greatest limiting factor for tree regeneration on seismic lines (van Rensen et al. 2015).

There are two distinct types of seismic lines, legacy lines (also called wide lines, conventional lines, or 2-D lines), and low-impact lines (also called narrow lines or 3-D lines) (Franklin, Filicetti & Nielsen, 2021; Echiverri, Macdonald & Nielsen, 2020). Legacy lines were the industry standard until the early 1990s; they are 5–10 m wide and spaced 300–500 m apart across the landscape (Franklin, Filicetti & Nielsen, 2021). Low-impact lines are a newer method of exploration and are only 1–4 m wide; however, they are spaced closer together at distances of 50–100 m apart (Franklin, Filicetti & Nielsen, 2021). Over the past three decades, there has been a switch to using low-impact seismic lines as they are known to bring less disturbance to the ecosystem, particularly to the original vegetation and soil properties (Dabros et al. 2017). Across the landscape, seismic lines cause ecosystem fragmentation by breaking up a previously undisturbed landscape into smaller, undisturbed regions (Davidson et al., 2020). The result of this fragmentation is an increase in peatlands bordering a disturbance, called ‘edge effects’, since the disturbance introduces a transitory edge where a disturbed site blends into an undisturbed site. Prior to 2016, seismic lines accounted for up to 80% of all peatland edge habitat in northern Alberta, meaning that many previously undisturbed peatlands are now crosshatched with these linear disturbances (Pattison et al., 2016).

While seismic lines are narrow, they are often built several kilometers long and can have an overall density of as high as 40 km/km^2 in Alberta’s peatlands; this density can be visualized as 50 m gridlines (Pattison et al. 2016; Filicetti et al. 2019). The failed regeneration of tree species on seismic lines is acknowledged and studied and it is still unknown why trees fail to regenerate; however, we know that human use exacerbates this issue as they continually introduce disturbance to the environment (Mercier et al. 2019). Currently, it is estimated that only 8.2% of seismic lines see recovery of tree species within 35 years post-disturbance (Lee & Boutin, 2006; van Rensen at al., 2015). While one might assume that seismic line corridors would revegetate quickly since they are narrow features, this is not a trend being observed in the field and some scientists estimate that it may take over 100 years post-disturbance to see a significant recovery of boreal peatland trees (Stevenson, Filicetti & Nielsen, 2019).

To determine why tree recovery rates remain small, it is important to identify the changes to peatland ecosystems caused by the creation of seismic lines. Seismic line disturbance can be separated into four categories of change: microtopography, soil and hydrology, vegetation, and wildlife (Davidson et al., 2020). Peatlands naturally form hummocks and hollows, which provide variance in topography and habitat. When seismic lines are created, hummocks and hollows are flattened and microtopography is simplified (Lovitt et al., 2019; Stevenson et al., 2019). Seismic line simplification is not yet widely studied, but the current estimate of topographical simplification is 20%, or 8 cm (Stevenson, Filicetti & Nielsen, 2019). When seismic lines flatten hummocks, they reduce dry areas that would better support tree establishment and growth and reduces the likelihood of natural forest regeneration (Caners & Lieffers, 2014; Lieffers et al., 2017).

A major disturbance to seismic soils and hydrology is compaction. When seismic lines are made, heavy machinery drives across the line and compacts the upper organic layers (Davidson et al., 2020). Since peat is a loose organic soil and highly susceptible to compaction, this negatively influences the soil structure and morphology and can decrease the saturated hydraulic conductivity of soil by 75% (Price, Heathwaite & Baird, 2003). Compaction can have many detrimental effects on peatland hydrology, including raising the water table, hindering sub-surface flow, and unbalancing nutrient ratios (Langdon, Dovciak & Leopold, 2020). These changes increase periods of saturation and flooding, which have a detrimental effect on the successful establishment of trees (Lieffers et al., 2017).

Seismic lines often also remove the existing ground layer vegetation on the site, resulting in highly disturbed vegetation communities. These disturbances affect the peatlands on either side of the seismic line as edge effects bleed into this space, affecting ecosystem processes and how species interact with the land and each other (Dabros et al. 2017). Due to the slow growth of peatland species and waterlogged conditions, peatland revegetation is a slow process (van Rensen et al. 2015). When seismic lines remove vegetation, there is now an opportunity for regrowth, which is further supported by increased light intensity due to the open forest canopy layer (Langdon, Dovciak & Leopold, 2020). However, early successional species outcompete the native vegetation and can lead to a successional shift in vegetation communities (Filicetti, Cody & Nielsen, 2019). Most peatland successional studies report a large increase in graminoids that include grasses, sedges, and reeds (Camill et al., 2010). However, some studies report an increase in certain Sphagnum as they profit from the open forest canopy post-disturbance (Pace et al., 2018). It is also suggested that seismic lines play a role in shifting mycorrhizal communities and associations, although the extent of this relationship is not clearly defined (Davidson et al., 2020). The type of seismic line is also an important factor when predicting natural recovery as low-impact lines saw a greater resurgence of herbaceous species within 2 m from the edge of the line and reached a 90% return of feathermosses; however, there was no significant recovery to microtopography, moisture levels and woody vegetation (Dabros & Higgins, 2022). All in all, it is rare for seismic lines to match the previous composition of vegetation communities after seismic line disturbance. This is especially true with tree and large shrub species, as these taller plants do not regrow to their original conditions, leaving the forest canopy open over the line. The lines remain open spaces, which impacts the way humans and animals interact with the system (Russell, Pendlebury & Ronson, 2016).

A critical and well-studied peatland species is the woodland caribou (Thiffault et al., 2013). Woodland caribou (*Rangifer tarandus caribou*) are a native species to Alberta whose habitat range includes boreal peatlands, they browse on lichens and graminoids (grasses and sedges) and use boreal peatlands as an escape from fast-moving predators like wolves (Rettie & Messier, 2000). Caribou use seismic lines as navigational pathways through peatlands; however, these corridors provide new opportunities for competition and predation (Latham et al. 2011). The primary competitor of caribou, white-tailed deer (*Odocoileus virginianus*) often encroach on caribou habitat through seismic lines, and this increase in available prey can sometimes increase local wolf populations (Thiffault et al., 2013). Caribou, as a species at risk, is of major importance to local governments and Indigenous communities and for this reason many seismic line restoration projects focus on the benefits to caribou populations (Dickie et al. 2017). For example, due to the extent of habitat disturbance and declining population, the Cold Lake Boreal Woodland Caribou herd is considered to be 'Not Self-Sustaining' (Russell, Pendlebury & Ronson, 2016). A key predator of caribou, the Grey Wolf (*Canis lupus*), has a range that intersects the Cold Lake caribou habitat (Latham et al., 2013). Since caribou are often drawn to the open canopies of seismic lines to forage for sedges and young plants, wolf packs are more successful in their hunts on seismic lines than in forested areas since they have the advantage of speed along seismic lines (Latham et al., 2013). Therefore, reducing disturbance, including active treatment of seismic lines to limit predator movement, is an important part of caribou recovery plans (Government of Alberta, 2017).

1.5 Restoration Practice for Seismic Lines

The restoration of forests and forested peatlands are a major concern in Alberta; however, the primary focus is on restoring forested areas serving as caribou habitat (Lieffers et al., 2017; Davidson et al., 2020). Therefore, while seismic line recovery might be included in an official caribou restoration plan, there are currently no official plans or programs designed to restore seismic lines at a landscape level (Lieffers et al., 2017; Davidson et al., 2020). However, the need for new rigorous seismic line restoration procedures may incite new monitoring program objectives, as introduced in Ficken et al. (2022)'s conceptual monitoring model. Most seismic lines were left to recover naturally by removing any human disturbance in a laissez-faire method of restoration; however, this method has not shown positive results in returning ecosystem functions to peatlands (Lee and Boutin, 2006). As more seismic lines remain open and scar the landscape, stakeholders in caribou habitat protection have arisen to identify the underlying issues, prevent further habitat loss, and restore seismic line tree cover (Davidson et al., 2020). The leading stakeholders in these restoration activities are often private sector oil and gas companies, but there has been a recent increase of interest from the public and governmental programs to support and fully realize restoration plans (Davidson et al., 2020; Thiffault et al., 2013). Traditional restoration efforts are expensive, often reaching CAD$ 12,500/km of seismic line recovery (Filicetti et al. 2019). These high costs are associated with the linear shape of seismic lines which increase travelling distances, and the remoteness of many seismic lines, some of which require fly-in access (Filicetti, Cody & Nielsen, 2019). With some parts of Alberta reaching a seismic line density of 40 km/km^2, these costs are calculated to reach into the billions for province-wide restoration (Hebblewhite, 2017). Due to this economic limitation, it is essential to fully understand how the ecosystem responds to seismic line restoration practices prior to restoration efforts.

When discussing restoration, it is important to set clear goals and objectives. Many long-term restoration goals center around supporting caribou populations while short-term goals focus on mitigating further human disturbance, protecting key caribou habitats and reducing forest edges through tree regeneration on lines (Finnegan, MacNearney & Pigeon, 2018). One downside to restoration efforts is that they may increase human disturbance on the line, especially compaction effects as crews work to apply restoration treatments (Echiverri, Macdonald & Nielsen, 2020). Due to the overall slow regeneration of soils and vegetation in peatlands, this disturbance may have unintended detriments to seismic lines recovery. However, it is generally acknowledged that restoration has become a necessity to restore tree populations since many seismic lines are not regenerating independently (Filicetti, Cody & Nielsen, 2019). On well pads, which are rectangular disturbances caused by oil industry activities, one tree restoration goal is to plant seedlings with a density of 3000 stems/hectare, however there is no standard density for seismic line goals (Filicetti, Lapointe & Nielsen, 2021). Ongoing restoration projects, like those led by Cenovus Energy, focus on using mechanical site preparation (MSP) to mitigate the detrimental effects of seismic line disturbance and encourage tree establishment

(Filicetti, Cody & Nielsen, 2019). The existing literature on these methods and their effectiveness in boreal treed peatlands is not well established, increasing the need for further study and examination of MSP in this environment (Filicetti, Cody & Nielsen, 2019).

1.5.1 Mounding Practices

In the context of environmental restoration, MSP is a term used to describe any activity that alters the land in order to provide suitable habitat and encourage tree seedling regrowth (Löf et al. 2012). There are many different methods of MSP, including scarification, subsoiling, stem bending, ripping, and mounding (Dassot & Collet, 2020). Mounding refers to the practice of altering soils to create sections of higher elevation, mimicking the natural hummock/hollow pattern often observed in peatlands and altering the microtopography of the ecosystem (Sutton, 1993). Generally, the goal of these mounds is to provide an elevated habitat for tree seedlings, therefore, being farther removed from the water table, and providing more space for root growth (Von der Gonna, 1992). Overall, most studies agree that mounding is beneficial to tree establishment and growth, with one extensive study identifying that, compared to untreated seismic lines, mounding increased tree seedling density by 160% at a total density of 12,290 stems/ha (Filicetti, Cody & Nielsen, 2019).

Mounding practices likely originated from an agricultural context, where elevating the soil in a wetted landscape would increase the usability of land for crops (Sutton, 1993). In a forest management context, mounding has been practiced for centuries across Europe (Sutton, 1993). There are records from the 19th century in countries like Germany, Prussia, Belgium, and Scotland where specific mounding practices were developed and published (Sutton, 1993). Another recent development in mounding practices was the invention of ‘turf-planting’ by Ford-Robertson in 1971. This mounding practice involved cutting a square piece of turf and laying it vegetation-side down (Sutton, 1993). ‘Inverted mounding’ is a term coined by McMinn in 1983 to describe a ‘turf-planting’ mound that is further capped with a 5- to 20-cm layer of mineral soil. This capping practice made the mound a rounder shape, which is more frequently used in mounding practices today. The term ‘inverted mounding’ was not popularized, and other names like ‘micro-bedding’, ‘berms’, ‘capped mounds’, ‘ridge mounds’ or plainly, just ‘mounds’ were used more frequently in a silvicultural context (Sutton, 1993).

While mounding is well-studied in silvicultural activities, it is a fairly new MSP method in boreal peatlands (Davidson et al., 2020). The earliest found study on the effects of mounding in boreal peatlands is Silfverberg (1995) that identified the effects of mounding and fertilization of trees in a drained peatland. This study concluded that mounding supported planted conifers; fertilization increased the chances of successful establishment but did not provide a benefit to overall seedling growth (Silfverberg, 1995). The next study on conifer establishment in drained peatlands was Takyi and Hillman (2000) that looked at the effectiveness of reforesting drained peatlands with conifer plantations. This study effectively dismissed mounding as an effective method for growing timber stocks (Takyi & Hillman, 2000). Both of these studies examined tree regeneration on drained peatlands, and it wasn't until Lafleur et al. (2011) that non-drained peatlands were studied regarding MSP and tree regeneration. This study may have been the first to acknowledge mounding as a method to promote tree regeneration in peatland ecosystems and concluded that any method of MSP provided a 15% increase in seedling height over five years (Lafleur et al., 2011).

While mounding practices are relatively new to peatland restoration, their effects on boreal peatlands are gaining attention in the field of restoration ecology of Alberta's peatlands, particularly related to restoration of seismic lines and exploration well-sites. From 2011 to today, there has been an exponential increase in scientific interest in mounding practices in boreal peatlands. Mounds on peatland seismic lines are known to have the following four benefits. Firstly, mounds expose new soil and nutrients by mixing the soil profiles (Sutherland and Foreman 1995). Secondly, a mound may create an ideal, unused space for seedling roots to expand without any competition (Örlander et al. 1990). Thirdly, if vegetation is removed from the mound, it will limit inter-species competition and allow the tree seedlings to monopolize soil nutrients (Staples et al. 1999). Finally, the elevated space of mounds places them further above the water table, creating a drier environment better suited to tree establishment and growth (Caners et al. 2019).

Unfortunately, there are also some associated detriments to mounding. Most importantly, mounding is another form of human disturbance that impacts the health and integrity of the ecosystem (Smolander & Heiskanen, 2007). This will likely lead to the increased organic matter decomposition and release of greenhouse gasses (GHG), thereby weakening the carbon capture and storage benefits of the peatland (Smolander & Heiskanen, 2007). It has also been suggested that current mounding methods are not recreating mounds to an adequate microtopographical standard, and mounds are still less elevated than natural hummock features (Pinzon, Dabros & Hoffman, 2022). Also, the benefits of mound elevation that are critical for tree establishment may be reduced over time as unstable mounds subside or erode away (Lieffers et al., 2017). While some studies suggest that mounding treatments support tree establishment and growth, the exact reasons for this support are not fully understood (Davidson et al., 2020). Since there are known benefits and detriments to different mounding methods, it is essential to choose the most appropriate treatment for local recovery. Some studies imply that while mounding treatments may benefit tree regeneration, the impacts to other essential ecosystem functions outweigh this benefit (Pinzon, Dabros & Hoffman, 2022).

There are dozens of different methods used to create mounds in the field, each one having unique characteristics that can influence tree establishment and growth. For example, 'inverse' or 'traditional' mounding is made by digging a hole on the seismic line and placing the soil vegetation-side-down on the flat of the line (Filicetti, Cody & Nielsen, 2019). This methodology focuses on removing competitive vegetation to promote seedling growth. However, recent studies have shown that these inverted mounds are prone to decompose peat at a faster rate with lower C/N ratios (Kleinke, 2022). In this case, the detriments of exposing peat soil may outweigh the benefits of reducing inter-species competition. This type of mound has also been found to remove existing bryophytes during MSP and hinder their regrowth up to three years post-mounding (Echiverri, Macdonald & Nielsen, 2022).

In contrast to inverted mounding, there are many other mound types that do not invert the soil profile: namely 'inline' (or 'upright') mounding, and 'hummock transfer' mounding. These two mounding methods retain their soil profiles and the existing vegetation on the line, which have been shown to result in no significant change in soil C/N ratios when compared to adjacent undisturbed peat profiles (Kleinke, 2022). To further explain, inline mounds are created in a similar way to inverted mounding, but when placing the mounds, the soil is placed vegetation-side up. The 'hummock transfer' mound methodology removes an existing hummock from the undisturbed peatland and transplants it on the line; this method actively tries to keep a strong and diverse vegetation community to support tree growth (Echiverri, Macdonald & Nielsen, 2020).

However, these mounding methods may reduce the peatlands function of carbon sequestration as peatland areas treated with both inline and hummock transfer mounding were found to have decreased CO_2 uptake and increased CH_4 emissions compared to untreated seismic lines sites two years post-mounding (Schmidt, Davidson & Strack, 2022). In contrast, a study on general MSP and mounding methods identified that disturbed peatlands may require a longer recovery period post-mounding (Murray et al., 2021). They concluded that we should expect carbon loss on seismic lines treated with MSP methods but after a 9-year recovery period, the system will regain a carbon cycle similar to undisturbed regions (Murray et al., 2021).

Mounding can also be completed by creating linear features with a hoe, board, or ripping shank; this methodology can be called 'rip and lift' as it involves dragging soil in a straight line to form a folded mound and a linear hole on the landscape. In this methodology, the disturbance to the landscape is more widely spread but the soil profile and vegetation are disturbed. Vodopija's (2021) study made several observations about Rip and Lift mound characteristics in comparison with Inline and Hummock Transfer mounds. Altogether, Rip and Lift mounds were found to be wetter and decomposing at a faster rate than other non-traditional mounds but did not show significant differences in planted seedling growth rates (Vodopija, 2021). This MSP method is relatively new in peatland ecosystems and little else is known about their impacts on boreal peatland ecosystems.

The end goal of MSP is to create an ideal microsite to support tree seedling growth, since past studies have shown that microtopography after seismic line disturbance is unsuitable for tree growth. However, there have been new studies that examined if a targeted planting and/or fertilizing approach may provide superior conditions for tree seedlings without the need for MSP (Pinzon, Dabros & Hoffman, 2022). This approach may also eliminate the detrimental effects on seismic lines treated by MSP such as declines in carbon sequestration and shifts in soil nutrient exchanges (Pinzon, Dabros & Hoffman, 2022). While the procedures, equipment and physical results of MSP methods may vary across treatments, the overall objective of these practices is to provide a superior habitat for tree seedlings by reducing the impacts of past human disturbances on seismic lines.

1.6 Thesis Objectives

Boreal forest peatlands are an important ecosystem that provide numerous benefits to humans and the environment. Today, the largest area of disturbance in Alberta’s peatlands are seismic lines, which disturb ecosystem functions and often have slow or delayed natural recovery of tree cover. As restoration projects increase and expand in northern Alberta’s peatlands, the concept of mounding as a strategy for new tree establishment becomes more important. There are many unknowns about how mounding practices affect the recovery of native trees on seismic lines. There have been previous studies on how mounding practices affect different environmental components of peatlands and previous studies comparing mounding success with unrestored seismic lines. However, there are few studies that compare different mounding methods, especially within the context of tree regeneration at the mound scale.

To fill this knowledge gap, my research project will examine the key physical and environmental characteristics of four unique mounding methods that may support or limit tree seedling establishment and growth on seismic lines. Additionally, these mounding methods will be compared to unmounded seismic lines and undisturbed natural areas. Through this examination of mound characteristics, the goal is to identify key supporting and limiting factors to seedling growth.

Within this project scope, there are five key research goals:

Firstly, to identify the key characteristics and attributes of different mounding methods. Through this examination, I will identify key physical characteristics of mounds and the secondary characteristics of the mound surroundings. With this information, I can describe the average microenvironment hosted on a single mound (Chapter 3).

Secondly, to identify patterns in seedling survivability across mounding methods. By identifying survivability, I can understand the necessary conditions for the initial survival (1–2 years) of seedlings post-planting, which can be used to inform future restoration projects (Chapter 4, Chapter 5).

Thirdly, to identify patterns in seedling growth over a two-year period. By identifying patterns of growth and cross-referencing these patterns with surrounding mound conditions, I can understand the mound attributes that support or limit growth within two years post-planting. This information can be used to inform future restoration projects and provide estimates for the initial growth of seedlings (Chapter 4, Chapter 5).

Fourthly, to identify any differences in survivability and growth of tree seedlings across two peatland tree species *Picea mariana* (black spruce) and *Larix laricina* (tamarack). By understanding the difference between these species, I can provide information on the benefits and detriments of planting each species based on a restoration project's environmental conditions, MSP method, or vegetation communities (Chapter 5).

Fifthly, to identify any difference in survivability and growth when tree seedlings are fertilized at the time of planting. By understanding the impacts of fertilization of tree seedlings, I can better understand the benefits and detriments of employing fertilizer during restoration projects with both black spruce and tamarack seedlings (Chapter 5).

Chapter 2: Study Sites and Methodology

2.1 Study Sites

2.1.1 Brazeau Study Site

<u>Site Location:</u>

The Brazeau study site is located on the western side of Sunchild Road, approximately 10 km southwest of the Brazeau Dam, within Brazeau County, AB (52°53'21.4"N; 115°32'57.0"W). The site is comprised of two seismic lines that run perpendicular to each other and intersect, forming a cross, with an additional line running northeast-southwest that was not part of the present study. One study line runs east to west (Brazeau West) while the other runs north to south, this line further splits into its northern half (Brazeau North) and its southern half (Brazeau South). The Brazeau West seismic line is mounded and planted for a length of 1250 m with a width of approximately 4.4 m, forming a study area of ~0.55 ha. The Brazeau North and South seismic line is mounded and planted for a length of 1800 m and an approximate width of 5.9 m, forming an area of ~1.06 ha. This complex has three entry points, one at each of the north, south and east line extremities. The southern entrance is the only entry point with direct road access.

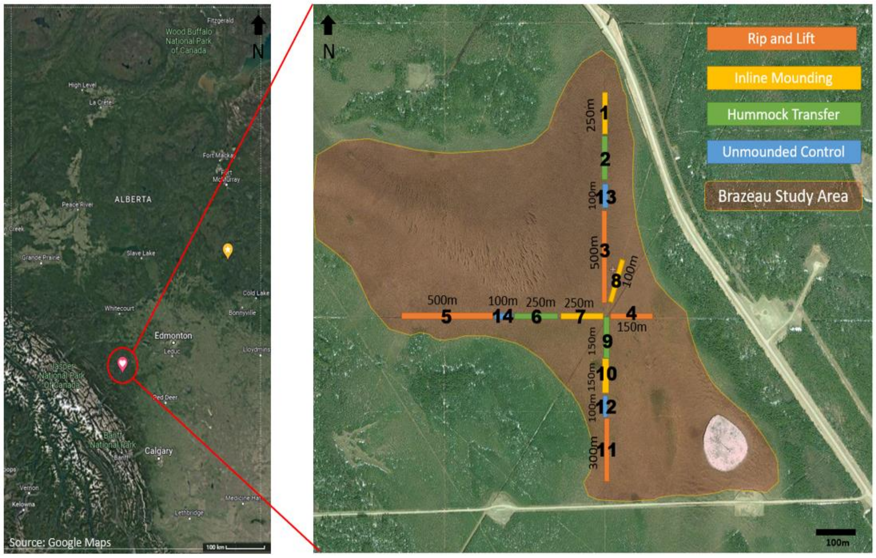

Figure 2.1: Map of the study site location in Brazeau County, Alberta. The mounding treatment methods are colour-coded on the site map. The site map numbers indicate the sub-site locations.

The Brazeau site is a boreal forested peatland lying within the Lower Foothills ecoregion, east of the Rocky Mountains (Alberta Agriculture and Forestry, 2020). The peatland can be further classified as a fen, with a north-south transition from rich to poor fen across the site. Brazeau North is a rich fen with a pore water pH of 7.3 and electrical conductivity of 224.55 ± 75.99 μS cm^{-1}, Brazeau South is a poor fen with a pore water pH of 5.9 and electrical conductivity of 71.75 ± 86.90 μS cm^{-1} (Vodopija, 2021). This transition affects the predominant bryophyte cover, as true mosses are more prevalent in the northern rich fen and Sphagnum moss dominates the southern poor fen. Throughout the site, sedges are common in the understory while the canopy vegetation is dominated by two tree species, Black Spruce (*Picea mariana*) and Tamarack (*Larix laricina*).

The climate in this region is continental (Dfb) under the Köppen climate classification (Encyclopedia Britannica, 2022). The daily temperature from 2019 to 2021 averaged between 17 °C and -20 °C but the annual temperature range extends from a high of 40 °C to a low of -40 °C (Alberta Climate Information Service, 2022). The normal accumulated precipitation from April to October in this region is ~550 mm of rainfall. During these months in the years of restoration, planting, and assessment (2019-2021) the region received a total of ~700 mm of rain in 2019, ~590 mm in 2020 and only ~460 mm in 2021 (Alberta Climate Information Service, 2022). Over the course of the mounding project, the new seedlings were planted at the end of a very wet summer, had their first full growing season with plenty of rainfall and were measured after experiencing their first drier than normal season.

History of Disturbance and Restoration Treatments:

The Brazeau seismic lines are estimated to have been created prior to 1982. While there are no public records of the original seismic surveying, these seismic lines are visible on historic satellite images starting from the year 1982. The first known disturbance to the Brazeau site since its creation was the mounding restoration project in March 2019. Since then, Brazeau has become a study site used by university and government researchers examining the impact of mounding on seismic lines in treed peatland areas. A variety of environmental factors have been studied and recorded at this site, including meteorological conditions, soil bulk density, water table, above- and below-ground biomass, and other factors relating to the soil, hydrology and vegetation (Kleinke et al., 2022; Schmidt et al, 2022; Vodopija, 2021). Site disturbances related to this research include compression of the peat from foot traffic and the installation of permanent collars for measuring carbon and greenhouse gas exchange, wells, and platforms.

The mounding of the Brazeau seismic lines was conducted in late March 2019. This makes the Brazeau seismic lines at least 37 years old at the time of restoration. Four unique mounding and planting methods were staggered across the site, spreading mounding types evenly across the Brazeau West, North and South lines (Figure 2.1). These methods include Rip and Lift, Inline Mounding, Hummock Transfer and Unmounded treatments. The Rip and Lift mounding was made using a KOMATSU PC200 Trackhoe Excavator equipped with a 1m-long single toothed ripping shank (Vodopija, 2021). The ripping shank was dragged across select portions of the line, creating linear trenches approximately 1 m deep and 1 m long (Vodopija, 2021). Through this dragging motion, the peat is gathered and folded into a mound at the end of the trench, creating an elevated area of topography. The Inline Mounding and Hummock Transfer mounding were made using the KOMATSU PC200 with a bucket attachment (Vodopija, 2021). The inline mounding was accomplished by digging a hole on the seismic line and placing the dug material vegetation-side-up next to the hole. The Hummock Transfer was completed by transplanting an existing hummock from the natural areas adjacent to the seismic line; hummocks were chosen from a zone at most 20 m deep into the forest (Vodopija, 2021). These methods are best achieved when the peat is still partially frozen in the spring since frozen soil will hold its form more effectively during transplanting. In June 2019, Inline and Hummock Transfer mounds had an average mound height of 20 cm, and the resulting holes were an average of 19 cm deep for Inline Mounding and 10 cm deep for Hummock Transfer (Schmidt, 2021). Rip and Lift mound height was measured for the first time in summer 2020, with an average of 22.5 cm (Vodopija, 2021). As the name suggests, Unmounded site soils were not mechanically disturbed, and there are no mounds. However, they were driven over by the excavator during the creation of the mounding treatments, so all sites received similar amounts of compression from the weight of the machinery. At the time of mounding, the site was also treated with stem bending at a low density (Schmidt, 2021). Stem bending refers to a restoration practice that pulls down trees from the natural areas off the line and lays them down across open areas of the line. This strategy has two main purposes: 1) to revegetate the line as cones from fallen trees are now spread across the seismic line and 2) to make travel across the line more difficult which impedes fast travel, thereby reducing the speed advantage wolves have over caribou and, in populated regions, reduces human use of the seismic line (Schmidt, 2021).

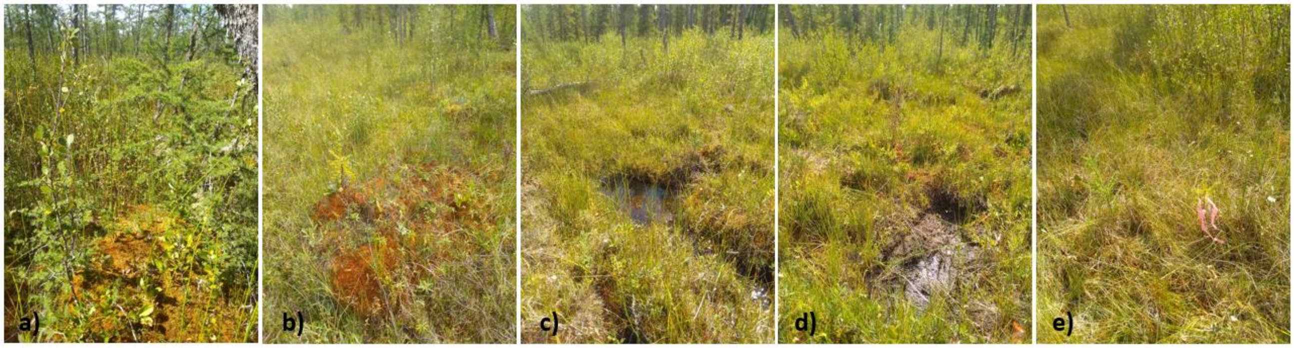

Figure 2.2: Photographs of the Brazeau study site and mounding treatments, showing (a) an undisturbed area off the seismic line, (b) a Hummock Transfer mound, (c) a Rip and Lift mound, (d) an Inline Mounding mound and, (e) an Unmounded section of the seismic line.

The Brazeau seismic lines were planted in August 2019, six months after the mounding. One black spruce and one tamarack seedling were planted on each mound within the Rip and Lift, Inline Mounding and Hummock Transfer treatments. In the Unmounded sections, seedlings were planted in pairs on areas with perceived higher elevations. The tree seedlings were planted by hand in pre-identified sections of seismic line and there was great variability in planting density across sections. This variability is likely due to the fact that trees were allocated to sampling plots based on plot length not total area. As shown below in Table 2, Unmounded sections had the highest seedling density (0.245 seedlings/m^2), followed by Rip and Lift (0.208 seedlings/m^2) and Hummock Transfer (0.180 seedlings/m^2) with Inline mounding as the most sparsely planted (0.168 seedlings/m^2). However, we also see patterns where the Brazeau North and Brazeau South lines are planted with a similar density while the Brazeau West line is much more sparsely planted.

Table 2.1: Summary of treatment plot area, seedling count and tree seedling density.

Treatment Plot	Section Length (m)	Average Line Width (m)	Average Area (m^2)	Seedling Count	Density (tree/m^2)	Density (tree/ha^2)
Unmounded	150	4.7	705	173	0.245	2453
Plot 13: Brazeau North	50	3.2	161	72	0.446	4461
Plot 14: Brazeau West	50	5.8	290	20	0.069	689
Plot 12-1: Brazeau South Unfertilized	25	4.6	114	43	0.374	3742
Plot 12-2: Brazeau South Fertilized	25	5.2	130	38	0.292	2917
Rip and Lift	525	4.9	2572	536	0.208	2084
Plot 3: Brazeau North	250	3.6	913	282	0.309	3087
Plot 4: Brazeau West	125	6.1	760	67	0.088	880
Plot 11-1: Brazeau South Unfertilized	75	4.6	346	110	0.317	3175
Plot 11-2: Brazeau South Fertilized	75	5.4	404	77	0.191	1905
Hummock Transfer	324	5.3	1717	309	0.180	1799
Plot 2: Brazeau North	125	3.6	454	126	0.277	2774
Plot 6: Brazeau West	125	5.7	710	69	0.097	971
Plot 9-1: Brazeau South Unfertilized	37	5.6	209	45	0.216	2156
Plot 9-2: Brazeau South Fertilized	37	6.1	227	69	0.304	3041
Inline Mounding	324	5.3	1717	288	0.168	1677
Plot 1: Brazeau North	125	3.4	425	77	0.181	1811
Plot 7: Brazeau West	125	5.9	738	71	0.096	962
Plot 10-1: Brazeau South Unfertilized	37	5.6	209	88	0.421	4212
Plot 10-2: Brazeau South Fertilized	37	6.1	227	52	0.229	2289
Inverse Mounding	1300	6.2	8060	139	0.017	172
Plot 17: LLB North	650	6.8	4422	64	0.014	144
Plot 19: LLB South	650	5.5	3553	75	0.021	211

On the Brazeau South line, half of each treatment was also fertilized during planting using small biodegradable bags of fertilizer prills. These prills are an NPK fertilizer with a known ratio of 20% N, 10% P and 8% K. Specifically, the nitrogen in the fertilizer was 17.64% urea N and only 2.36% ammoniacal N (Vodopija, 2021). The prills were wrapped in a 10 g tea bag with a slow-release coating (Vodopija, 2021). Two years post-planting, the bags had decomposed and the prills showed some evidence of dissolution. In total, 1700 trees were planted at Brazeau, with a subset of 260 trees planted with fertilizer. There are a total of 14 sub-sites within the Brazeau study site complex. Each mounding method is repeated on the Brazeau North, West and South lines, these 12 sub-sites have both planted and unplanted sections to allow for future studies assessing the effects of tree planting on seismic line tree density. These unplanted areas were excluded from the present study as the focus was on how mounding treatments and mound characteristics affect growth of planted seedlings. The final two sub-sites, sub-site 5 and sub-site 8 as shown on Figure 2.1, were not planted and have also been excluded from the present study.

2.1.2 Lac la Biche Study Site

Site Location:

The second study site, Lac La Biche, is comprised of two independent seismic lines running in an E-W direction. They are parallel to each other and spaced 2 km apart along the western side of HWY 881, halfway between the towns of Conklin and Imperial Mills, within Lac La Biche County, AB. The northern seismic line site, named LLB North (N55°14.5020'; W111°19.5711') is 630 m long and approximately 6.6 m wide, with an area of ~0.42 ha. The southern seismic line site, named LLB South, is located 2 km to the south. This seismic line site (N55°13.4217'; W111°19.0504'), is 580 m long and approximately 5.5 m wide, with an area of ~0.32 ha. There is one point of entry for each seismic line where they meet HWY 881 at the eastern extremity of the study site. It is also possible to walk between LLB North and LLB South across another seismic line running N-S that intersects both LLB lines.

Figure 2.3: Map of the study site location in Lac La Biche County, Alberta. The LLB North and LLB South seismic lines are highlighted on the site map.

The Lac La Biche site is categorized as a boreal treed peatland and a poor fen ecosystem. It is located within the Central Mixedwood ecoregion as defined by the Government of Alberta (Alberta Agriculture and Forestry, 2020). The predominant understory vegetation consists of Sphagnum mosses and sedges while the canopy is predominated by black spruce (*Picea mariana*) and tamarack (*Larix laricina*). This site is part of the Cold Lake Boreal Caribou Range, making it prime habitat for the boreal woodland caribou (*Rangifer tarandus caribou*) (Government of Alberta, 2017). In the Canadian Parks and Wilderness Society's 2016 draft report of Caribou Range Planning, it was estimated that 72% of the Cold Lake range has been disturbed from anthropogenic causes, which include linear disturbances like seismic lines and roads, as well as direct habitat loss from forestry practices (Government of Alberta, 2017).

The climate in this region is continental (Dfc) under the Köppen climate classification (Encyclopedia Britannica, 2022). The daily temperatures from 2019-2021 averaged between 22 °C and -32 °C but annually the range extends from a high of 35 °C to a low of -40 °C (Alberta Climate Information Service, 2022). The study site had a drier than average growing season in 2019, an average cumulative precipitation in 2020 and a very dry year in 2021. There was a total of ~450 mm of rain falling in the summer of 2019, ~490 mm in 2020 and ~360 mm in 2021

(Alberta Climate Information Service, 2022). To compare, the yearly normal for this region is ~500 mm of rainfall from April to October (Alberta Climate Information Service, 2022). Over the course of the mounding project, the new seedlings were planted in a dry year, had their first full growing season with average seasonal rainfall and were measured after experiencing their first extremely dry season.

Comparing precipitation between the Brazeau study site and the Lac La Biche study site, the Brazeau precipitation normal is 50 mm greater than Lac La Biche so it is expected that the Brazeau site receives more precipitation. In 2019, Brazeau had an extremely high volume of precipitation while Lac La Biche saw a very low volume of precipitation compared to their precipitation normals. In 2020, Brazeau remained wetter than average while Lac La Biche met the precipitation normal. In 2021, both regions suffered a dry summer with low precipitation volumes.

History of Disturbance:

The original year the Lac La Biche seismic lines were surveyed is unknown; however, using historical satellite imagery we can visually identify that these lines existed in 1989, making them approximately 7 years younger than the Brazeau lines. There have been no known disturbances or research studies conducted on these seismic lines since their creation. Given the remote location of the lines it is unlikely that they are being used for recreational purposes such as walking trails or snowmobiling. On site visits did not find any indication of human activity or other anthropogenic disturbances. The Lac La Biche seismic lines were chosen as eligible sites for mounding and planting restoration as part of the Woodlands North planning project led by Regional Industry Caribou Conservation (RICC) which was supported by the Boreal Ecosystem Recovery and Assessment (BERA) research partnership. As a peatland that supports both caribou and wolf ranges, this site qualifies as a research site to examine how seismic line restoration affects the predator-prey relationship between these two species.

The restoration activities on the Lac La Biche seismic lines were conducted in the summer of 2019, making the site 30 years old at the time of restoration. First, the seismic lines were mounded using a mounding method widely used over the past decade for seismic line restoration in peatlands called Inverse Mounding. Inverse mounding was the only treatment conducted at this site. Inverse mounds were made using an excavator with a bucket attachment, holes were dug on the line and then the dug material was placed vegetation-side-down next to the hole. At the time of mounding, the Inverse mounds are estimated to be up to 80 cm high with a diameter of 50 cm, based on the mounding practices employed in 2019 in the Lac La Biche region (Filicetti, Cody, & Neilsen, 2019).

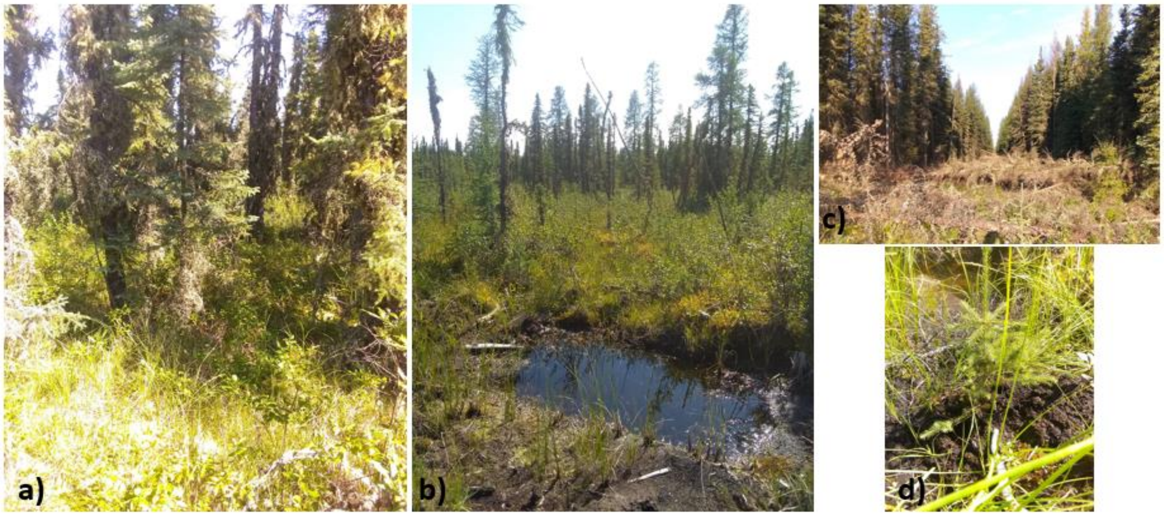

Figure 2.4: Photographs of the Lac La Biche study site and mounding treatment, showing (a) an undisturbed area off the seismic line, (b) an Inverse Mounding hole and mound, (c) the stem bending treatment on LLB North and, (d) a black spruce seedling planted on an Inverse mound.

After mounding, the LLB North line was treated with stem bending at a high density. While stem bending practices were employed at both seismic line sites, the high-density stem bending done at LLB North was immediately apparent, blocked direct travel and made it extremely difficult to walk along the line. Comparatively, at Brazeau the stem bending was difficult to identify, did not cross the entirety of the seismic line and did not impede travel along the line. Finally, both LLB North and LLB South were planted with one black spruce seedling on every Inverse mound. Using the total trees measured and the study site area, we can calculate the average planting density of trees at the site. These lines were planted with an average density of 0.017 seedlings/m^2, much lower than any other Brazeau section (Table 2.1). This lower density may be attributed to the fact that only one tree seedling was planted on each mound. In addition, the mounds at LLB North and LLB South seemed to be spaced farther apart than those at Brazeau. By limiting the numbers of trees planted to one tree per mound, the overall planting density of new seedlings is greatly reduced, and the overall tree presence is reduced.

2.2 Methods

2.2.1 Field Sampling Variables

Field sampling methodology was repeated for each planted seedling found within each treatment plot, in August-September 2021. A total of 1535 seedlings were measured; 1366 seedlings were measured at the Brazeau study site and 169 seedlings at the Lac La Biche study site (for seedling sample size by plot see Appendix A). All observed seedlings were measured in seismic line treatment plots located within Brazeau North, Brazeau South, Plot 4 of Brazeau West and LLB North. In the remaining seismic line treatment plots: Plots 6, 7 and 14 of Brazeau West and LLB South, a selective sampling approach using alternating 10 m sampled and 10 m omitted sections was used. With this methodology, seedlings were measured across the entire treatment plot, and it is assumed that the sample size recorded is half of the seedling population. This reduced sample size is clearly recorded in Table 2.1. Natural study plots did not have planted seedlings; representative seedling samples below-knee height were chosen in locations 30 m away from the seismic line for consistency and to avoid sampling areas affected by Hummock Transfer mounding.

Four categories of information were recorded for every planted seedling observed on the study site: (1) seismic line characteristics, (2) seedling characteristics, (3) mound characteristics and (4) vegetation characteristics. The seismic line characteristics of line orientation and line width were recorded every twenty-five seedlings. The seedling characteristics of height, first leader length and second leader length were measured with a tape measure. The leader length was always measured from the central leader which extends directly from the trunk of the seedling. The first leader length was measured from the tip of the terminal bud to the first whorl, and the second leader length was measured from the first whorl (lateral branches) to the second whorl. Tree condition was evaluated using the condition code classifications listed in the Provincial Restoration and Establishment Framework for Legacy Seismic Line in Alberta (Government of Alberta, 2018). Under this methodology, seedlings were classified under 'Healthy', 'Dieback with regrowth', 'Unhealthy', 'Dieback' and 'Dead'. Healthy trees are categorized by their green needles with no evidence of damage to buds and branches. Dieback occurs when leaders or terminal buds are damaged, missing, or dead; if there is evidence of regrowth of buds on damaged branches, this may indicate that dieback occurred last season and the seedling is recovering. Seedlings with discoloured needles, damage to the stem or large branches, and/or improper planting positions were classified under 'Unhealthy' while seedlings without any green needles or evidence of growth were classified as 'Dead'.

Mound elevation was recorded using a '*Smart Leveler 200-10-1-1 Bluetooth Construction Altimeter with 3D Mapping*'. Three elevations were taken, the first at the visibly highest location on the mound peak, the second directly beneath the tree seedling and the third on a visibly flat area of the line directly beside the elevated portions of the mound. The differences in elevation between these three altimeter measurements were calculated in Excel. The soil moisture measurements were taken at the same places as the altimeter elevations using a Delta-T Devices WET-2 Sensor. This sensor measures the soil at a depth of 6.5 to 6.8 cm. After field work, a soil sample was taken from one representative hummock or elevated area and one representative hollow or depression for further soil moisture calibration in the lab. The representative soil samples were left exposed to the air, they were measured with the same soil moisture probe and weighed repeatedly over the course of several weeks resulting in 9 results per sample. The samples were then dried and used to calculate volumetric water content (VWC) (Appendix B). The average VWC of each sample was used to calibrate the soil moisture results. Mound placement was recorded to identify if the mound was built in the center or sides of the seismic line. The tree placement was categorized as being near, central, or far away from the hole dug on the seismic line, as determined by where the tree was planted in comparison to the soil disturbances created in Rip and Lift, Inline Mounding and Inverse Mounding treatments.

Around each seedling assessed, the vegetation community and ground covers were described to the plant functional group level. Specifically, the cover of Sphagnum moss, other moss, lichen, forbs, graminoids, shrubs, trees, bare soil and standing water was assessed. I used a 30 cm^2 quadrat for moss and lichen and a 1 m^2 quadrat for vascular plants. Quadrats were placed with the seedling in the centre. Percent cover was estimated following a survey methodology from Dr. Scott J. Davidson, where percent cover is estimated to the nearest 5% (Davidson, et al., 2016). For communities with less than 10 individuals a scale of 1-5% was used, and 0.1% was used to acknowledge the presence of only one individual (Davidson, et al., 2016).

2.2.2 Laboratory Sampling Variables

A selection of Black Spruce seedlings was removed for root and ectomycorrhizal analysis. Three samples were removed from each Rip and Lift, Hummock Transfer, Inline

Mounding and Unmounded treatment plot, while six samples were removed from each fertilized sub-site on the Brazeau South line and Inverse Mounding treatment plot. Ectomycorrhizal (ECM) associations were analyzed following the standard methodology outlined in "*Working with Mycorrhizas in Forestry and Agriculture*" (Brundrett et al., 1996). With this standard, the tree roots were washed and sorted gently and measured for supporting root information such as root biomass, root length and root lateral spread. The root samples were cleared in a KOH 10% solution with a 15-minute autoclave liquid cycle at 121 °C. The root samples were then rinsed and stained in a solution of 0.03% w/v Chlorazol black E in lactoglycerol (1:1:1 lactic acid, glycerol, and distilled water) and another 15-minute autoclave liquid cycle at 121 °C. The stained roots were placed lengthwise on a slide and examined for the presence or absence of ECM association at 12 regular intervals of 6 mm. The percent of ECM presence over total measurement intervals was calculated as the measure of ECM associations per sample.

2.2.3 Statistical Analysis

The statistical software '*RStudio*' was used to complete all statistical analysis (Rstudio Team, 2020). Analysis of variance (ANOVA) tests were used to calculate the probability of difference of a select variable between mounding methods. The variables compared include seedling growth characteristics (cm), mound height (cm), soil moisture (VWC) and vegetation percent cover (%). As per the standards outlined by Muff et al. (2022) p-values below 0.1 were identified as pieces of evidence to support a difference between two groups where $p < 0.1$ is weak evidence, $p < 0.05$ is moderate evidence, $p < 0.01$ is strong evidence, and $p < 0.001$ is very strong evidence of statistical difference. Once evidence of difference was presented, a pairwise t-test was conducted using the "*emmeans*" package with a Tukey adjustment (Rstudio Team, 2020). To identify the environmental factors supporting or limiting seedling growth, a linear mixed effects model with backwards stepwise selection of fixed effects and a random factor of 'Plot' was used with the "*nlme*" and "*lme4*" packages in RStudio (Rstudio Team, 2020). All seismic line, mound, vegetation, and ECM factors were included in the stepwise selection process as effects and were eliminated if their partial p-value was less than 0.1. Using this model fitting approach, I eliminated a number of effects based on their fit in the current model. This reduced the multicollinearity of the model and provided a more accurate representation of correlation between the response variable (seedling growth) and the predictor variables (Kutner, Nachtsheim, & Neter, 2004).

Chapter 3: How Mounding Method Affects Mound Characteristics

3.1 Introduction

The goal of this chapter is to identify how different mounding methods affect site microtopography and microsite soil moisture and vegetation composition. The datasets used in this chapter include all measured microsites, totalling 1535 collection points across all five mounding methods plus Unmounded and Natural datapoints in both Brazeau and Lac La Biche sites. This provides an expansive population of microsite data to observe patterns in mound characteristics among mounding methods. There are three types of variables analyzed in this chapter, mound elevation, soil moisture and vegetation communities on the mound immediately surrounding seedling planting locations.

This chapter aims to answer the following research questions:

1. How does each mounding method alter the variance in microtopography on the seismic line?
2. To what extent does each mounding method create a drier soil profile around the planted tree seedling?
3. What patterns are observed in vegetation community composition on mounds across all mounding methods?

Mound elevation is the calculated difference in elevation from a nearby flat area of the landscape and the highest spot near the tree seedling. The hypotheses related to mound elevation were that Unmounded areas of the seismic line would have significantly less variation in microtopography than mounded sites and that Inverse mounds would be taller than all other mounds. Many previous research studies have concluded that mounding methods increase the site microtopography of unmounded seismic lines (Lieffers, Caners, & Ge, 2017). Therefore, the expectation is that the Unmounded area would have less microtopographic variation. The hypothesis that Inverse would be taller than non-traditional mounds comes from the known mechanical site preparation methods since Inverse mounds are often dug out to a depth of 1 m and the non-traditional mounds made at Brazeau were dug out to a depth of 30 cm. Therefore, even after the mounds settled on the line, Inverse mounds should be significantly taller.

Soil moisture was measured at three places for the peak of the mound, the base of the tree seedling and on nearby flat ground. Mounds were made to elevate soil further above the water table and many previous studies have observed a decrease in soil moisture on mounds (Lieffers, Caners, & Ge, 2017). The hypothesis related to soil moisture is that Hummock Transfer mounds would have the lowest soil moistures since these mounds are made of naturally formed hummocks. Therefore, these hummocks should have a natural soil profile and vegetation density that would maintain the low hummock soil moistures observed in undisturbed areas.

Vegetation composition at the mound microsite was measured considering seven plant functional types and two non-vegetative classes. The two hypotheses related to these variables were that Hummock Transfer mounds would have the highest density of shrubs and Inverse mounds would have the highest density of graminoids. Since shrub species prefer soil conditions similar to trees and are often found in low densities on seismic lines, it is hypothesized that the hummocks directly transplanted from the undisturbed areas would bring a higher density of surviving shrubs than found on any other type of mound (Finnegan, MacNearney, & Pigeon, 2018). Inverse mounds create the greatest area of soil disturbance since the soil is exposed on the top of the mound. Inverse mounds are also known to have slow moss recovery which increases the length of time that soils are exposed (Echiverri et al., 2020). This increased level of disturbance would provide a greater number of opportunities for fast growing species like graminoids to encroach on the seismic line (Urbina & Benavides, 2015).

3.2 Results

3.2.1 Mound Size and Subsidence

Natural hummock formations at the study sites are on average 20 cm tall, with an interquartile range of 15 to 23 cm (Figure 3.1). If the goal is to mimic the natural microtopography, mounding methodologies should strive to reach an average mound height within this range. The tallest sections of the Unmounded subsites fall below this range with an average mound height of 14.5 cm. The interquartile range of 11 to 18 cm also does not meet the Natural average indicating that most elevated areas in the unmounded treatment are shorter than the average mound height in the measured natural peatlands. The non-traditional mounding methods of Rip and Lift, Hummock Transfer, and Inline Mounding had the same average mound height of 18 cm and also showcased similar interquartile ranges from 12 to 23 cm (Figure 3.1).

These non-traditional mounds were the closest in size to the natural hummocks observed off the seismic lines. The traditional Inverse mounds were taller than all other mounds with an average of 23 cm and a range of 23 to 28 cm, making them taller than both the naturally formed and non-traditional hummocks. Mounding methods resulted in significant differences in mound heights (ANOVA, $F_{5,12}= 4.547$; $p=0.0147$) with strong evidence that Inverse mounds are significantly taller than Unmounded sections of the seismic line ($p=0.0067$). There is further weak evidence to suggest that the Unmounded seismic lines have smaller variance in topography than Natural sites ($p=0.0741$) and that Inline mounds are significantly smaller than Inverse mounds ($p=0.0968$). All other treatments were statistically similar (Figure 3.1).

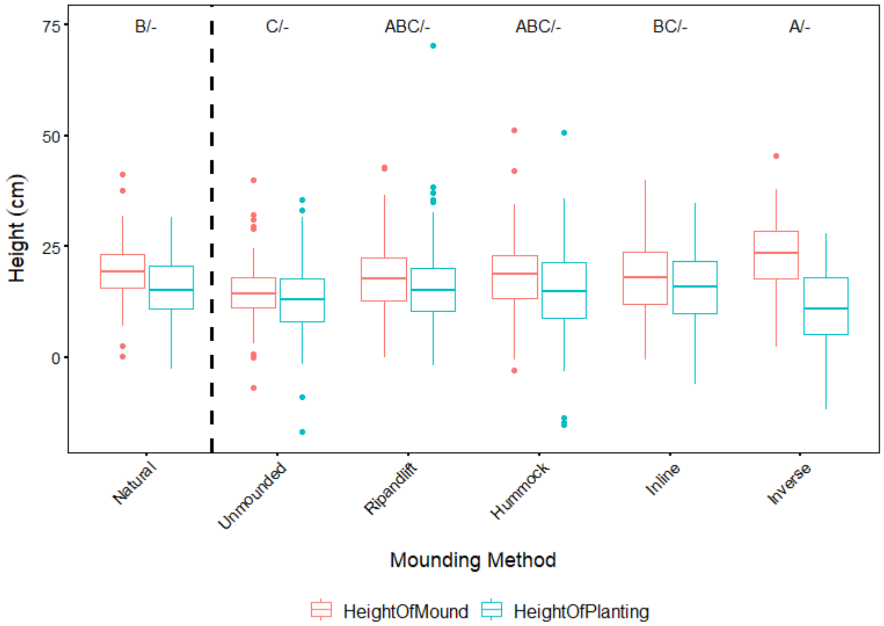

Figure 3.1: Mound height and the planting height of tree seedlings (cm) by mounding method. Significant differences displayed above in letter notation where treatments are significantly different (p<0.1) if no letters are shared.

If we consider that the Inline mounds and Hummock Transfer mounds were measured at an average of 20 cm tall in the summer of 2019, we can calculate a subsidence value of 10%. Similarly, with the estimation of Inverse mounds being created at 80 cm tall, we can calculate a subsidence value of 70%. It should be noted that Inverse mounds were not directly measured immediately after formation and that this height is assumed based on other studies. However, the depth of the hollows adjacent to the mounds suggested that this height is a reasonable assumption. Therefore, there is a large inconsistency between how non-traditional (Hummock

Transfer and Inline) and traditional (Inverse) mounds settle post-mounding. While Inverse mounding creates the tallest mounds, they are also more prone to subsidence on seismic lines.

Planting height refers to how high the seedling was growing on the mound; low or negative values indicate that trees are not well situated near the mound peak. Naturally established trees were growing at a height of 15 cm, which is within 5 cm of the average mound peak. The trees planted on Rip and Lift (15 cm), Hummock Transfer (15 cm) and Inline (16 cm) mounds were also planted at heights similar to naturally growing trees (Figure 3.1). The interquartile ranges of these four groups were also similar, with trees growing at elevations between 10 and 20 cm. On Inverse mounds, trees were growing at a lower height of 11 cm with an interquartile range of 5 to 18 cm. While a quarter of Inverse trees were planted at average Natural height, the majority of the trees on the Inverse mounds were measured far below average. Comparing overall planting height among mounding methods using ANOVA indicated no significant variation among treatments ($F_{5,12}$ =1.477 p=0.2679). While Figure 3.1 shows that Inverse trees were planted lower than any other mounding methods, this difference is not statistically significant.

3.2.2 Mound Soil Moisture

Soil moisture on flat portions of the Natural area had an average wetness of 31% VWC. The unmounded seismic line areas had an average VWC of 73%, supporting the conclusion that seismic lines are wetter than undisturbed regions (Figure 3.2). Mounding restoration practices do not affect the overall wetness of the flat portion of the seismic lines to a large extent. There was an average VWC of 68% beside Rip and Lift mounds, 78% VWC beside Hummock Transfer mounds and 69% VWC beside Inline mounds. The areas beside Inverse mounds had an average VWC of 65%, making these seismic lines drier than all other mounded areas. An ANOVA test ($F_{5,12}$=6.837; p=0.0031) indicated the flat areas in Natural sites were significantly drier than all seismic line sites. Strong evidence of difference was observed between Natural flat areas and flat areas in Unmounded (p=0.0040) and Hummock Transfer (p=0.0029), moderate evidence was presented for Rip and Lift (p=0.015) and Inline Mounding (p=0.0222), while weak evidence supported the difference between the Natural flat areas with flat areas at Inverse Mounding (p=0.0556).

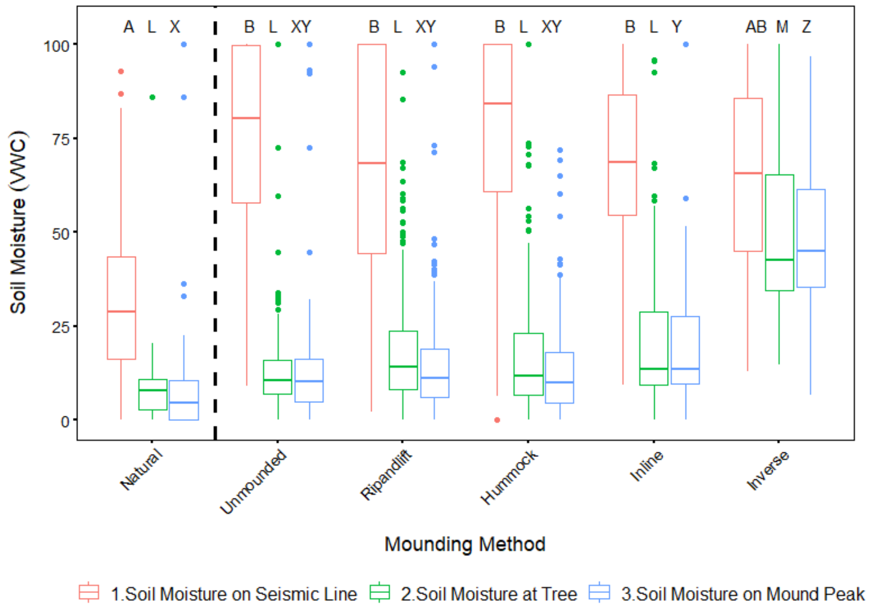

Figure 3.2: Soil moisture on the flat area beside the mound, soil moisture at the base of the tree seedling and soil moisture at the mound peak (VWC) by mounding method. Significant differences (p<0.1) are displayed above in letter notation.

Soil moisture measured at the tree is an indication of the moisture conditions of the planted seedling. In Natural areas, trees were growing in soil with an average soil moisture of 8% VWC, a value four times smaller than the average from flat locations of the landscape. The soil moisture measurements for the flat areas and the base of the tree were always taken within 1 m of each other. This indicates that there is a large difference in soil moisture within a small area of microtopography and that natural trees are growing in the areas with much drier conditions. The unmounded trees had an average soil VWC of 13%. There is an average of 17% VWC in soil at Rip and Lift seedlings, 17% VWC at Hummock Transfer seedlings, and 20% VWC at Inline seedlings (Figure 3.2). Therefore, there was a pattern of trees planted on non-traditional mounds growing in slightly wetter conditions that those planted in the Unmounded seismic line sections. The areas beside Inverse seedlings had an average VWC of 50%, on average two-and-a-half times more wet than any other seismic line site. While the flat of Inverse sites had the lowest VWC, their seedlings were growing in soil that had the highest average VWC. An ANOVA test indicated that the soil moisture at the seedlings was significantly wetter in Inverse Mounding sections than any other section ($F_{5,12}$=11.827; p=0.0003). Very strong evidence of higher seedling VWC at Inverse Mounding compared to the Natural Site (p=0.0001) and Unmounded areas (p=0.0005), while strong evidence was presented for Inline Mounding (p=0.0042), Rip and Lift (p=0.0017) and Hummock Transfer (p=0.0012).

Soil moisture at the peak of naturally formed hummocks was measured with an average VWC of 8%, showing no difference between the soil moisture at the tree and mound peak. The highest places on Unmounded sections had an average VWC of 14%, while the non-traditional mound peaks had similar VWC of 14, 14 and 19 % at Rip and Lift, Hummock Transfer, and Inline Mounding, respectively. The Inverse Mound peaks were the wettest with an average VWC of 48%. Overall, every section showed a slight decrease in soil VWC from the area around the tree to the peak of the mound (Figure 3.2). Inverse mounds remained the wettest but Inline mounds were also slightly wetter than other non-traditional mound peaks. An ANOVA test indicated that the soil moisture at the mound peaks was significantly different between treatments ($F_{5,12}$=15.346; p=0.0001). This was due to significantly higher VWC on the tops of Inverse Mounds with very strong evidence of difference in comparison with the Natural (p<0.0001), Unmounded (p=0.0002), Rip and Lift (p=0.0003) and Hummock Transfer (p=0.0002) and strong evidence for Inline Mounding (p=0.0016). There was also weak evidence to suggest that Inline Mounding sites were wetter than Natural areas (p=0.0909).

3.2.3 Vegetation Communities on Mounds

Using the average Sphagnum cover of the Natural areas as a standard, Rip and Lift and Inline mounding treatments had greater Sphagnum cover while Unmounded and Inverse mounding had less Sphagnum cover (Table 3.3). However, the cover of Sphagnum was highly variable between individual mounds as many mounding treatments had a wide interquartile range of 0% to 100%. Rip and Lift mounds had the highest average and a small interquartile range, showing a greater overall Sphagnum cover than any other treatment. The Sphagnum cover of Inverse mounds had very different data patterns with a low average of 0.6% Sphagnum cover and a maximum cover of 25%. This average is positively skewed since most Inverse mounds had no Sphagnum cover at all; there is a clear lack of Sphagnum cover on Inverse mounds. However, comparing amongst mounding methods using ANOVA indicated no significant variation among treatments ($F_{5,12}$=0.907; p=0.5079).

Table 3.1: Percent cover vegetation community statistics by mounding method (%). All values are estimations of percent cover and noted in percentage. Statistical significance of p-values is displayed using letter notation in the grey rows.

Percent Cover Values	**Natural**	**Unmounded**	**Rip and Lift**	**Hummock Transfer**	**Inline**	**Inverse**
Sphagnum						
Average	59.8	45.2	70.7	49.9	67.3	0.6
Interquartile Range	0-100	0-100	30-100	0-100	0-100	0-0
Standard Deviation	46.4	49	39.8	47.8	43.7	2.8
Other mosses						
Average	30.4	40.8	6.4	38.5	12.5	10.8
Interquartile Range	0-77.5	0-90	0-2	0-95	0-10	0-15
Standard Deviation	42.4	42.8	17.9	45.1	24.7	17
Lichen						
Average	0.4	0.2	0.1	0.3	0.0	0.2
Interquartile Range	0-0	0-0	0-0	0-0	0-0	0-0
Standard Deviation	1.8	1.6	0.5	2.1	0.1	1.3
Graminoid						
Average	7.6	19.8	16.5	15.9	13.3	21.2
Interquartile Range	2-10	5-20	10-25	10-20	5-20	10-30
Standard Deviation	12.2	14.6	17.2	8.0	6.7	18.2
Forb						
Average	7.7	9.5	9.2	4.9	7.6	7.4
Interquartile Range	2-15	5-15	5-15	1-10	3-10	2-10
Standard Deviation	8.0	6.3	5.9	4.6	6.1	7.7
Shrub	**a**	**ab**	**ab**	**ab**	**ab**	**b**
Average	19.4	10.7	12.4	11.2	13.5	2.4
Interquartile Range	10-25	4-15	5-15	5-15	5-15	0-3
Standard Deviation	12.1	8.2	9.4	8.5	10.5	4.5
Tree	**a**	**b**	**b**	**b**	**b**	**ab**
Average	7.6	0.2	0.8	1.1	1.6	1.5
Interquartile Range	0.1-10	0-0.1	0.1-0.1	0.1-0.1	0.1-2	0-0
Standard Deviation	8.9	0.6	2.6	3.0	2.6	4.2
Water						
Average	0.0	0.1	0.6	2.4	1.3	2.5
Interquartile Range	0-0	0-0	0-0	0-1	0-0	0-1.5
Standard Deviation	0.1	0.5	2.1	6.4	4.4	5.8
Bare Soil	**a**	**a**	**a**	**a**	**a**	**b**
Average	4.2	2.4	3.1	4.2	3.4	58.4
Interquartile Range	0-5	0-2	0-4	0-5	0-3	35-80
Standard Deviation	6.4	4.7	5.8	6.9	7.0	25.1
Total Vegetation	**a**	**a**	**a**	**a**	**a**	**b**
Average	96.6	98.0	96.2	94.5	94.9	42.0
Interquartile Range	95.78-100	97.9-100	95.9-100	93-100	95.72-100	22.9-60
Standard Deviation	6.6	3.8	7.2	9.6	11.1	22.4
Total Non-vegetation	**a**	**a**	**a**	**a**	**a**	**b**
Average	3.4	2.0	3.8	5.5	5.1	58.0
Interquartile Range	0-4.23	0-2.1	0-4.1	0-7	0-4.28	40-77.1
Standard Deviation	6.6	3.8	7.2	9.6	11.1	22.4

Overall, there is less moss cover than Sphagnum at all sites, and mounding treatments with greater moss cover had less Sphagnum cover (Table 3.3). One pattern observed is that naturally formed mounds had a much higher range of moss covers than mounds with built soil profiles. These naturally formed mounds include the Natural, Unmounded and Hummock Transfer sites. An ANOVA test for moss cover across treatments did not show any evidence of significant variation ($F_{5,12}$=0.871; p=0.5280). However, when both Sphagnum and other moss covers are considered together, total moss cover among mounding methods becomes highly significant different ($F_{5,12}$=7.416; p=0.0022). With this consideration, there is strong evidence that Inverse mounds have less bryophyte cover than all other sites ($0.0092 > p < 0.0016$). We can also see that when Sphagnum and true mosses cover statistics are combined, there was almost a complete ground cover of moss at Natural and Unmounded plots.

In terms of graminoid species presence, there was a noticeable increase in cover from natural areas to seismic lines as Unmounded plots had the highest cover of any treatment type. Non-traditional mounding methods seemed to reduce the density of graminoids while Inverse Mounding did not show a difference and retained a graminoid density similar to Unmounded areas (Table 3.3). This demonstrates that non-traditional mounds may mitigate the encroachment of graminoids species post-disturbance. Overall, using ANOVA to compare treatments, indicated no significant variation ($F_{5,12}$=1.670; p=0.216).

Shrub cover followed a pattern similar to graminoid cover. Unmounded sections of the seismic line had only recovered half of the shrub cover observed in Natural sections. After non-traditional mounding methods were employed on the seismic line, two thirds of the undisturbed shrub density returned to the mounds on site. The Inverse mounding method had the lowest shrub cover of all restoration methods. These mounds only recovered one tenth of undisturbed shrub density and were the only restoration method to have less shrub cover than unrestored sections of seismic lines. Comparing overall shrub cover amongst mounding methods using ANOVA indicated significant variation amongst treatments ($F_{5,12}$=3.062; p=0.0446), where the Natural comparison mounds had significantly greater cover than the Inverse mounds (p=0.031) and all other treatments were statistically similar (Table 3.3).

The percent cover of trees on the mounds was high in Natural areas where many trees grow together in small groups. Seismic line sites did not showcase much grouping of seedlings;

however, since these surveys are only two years post-mounding this pattern may still emerge. There was moderate to strong evidence (ANOVA, $F_{5,12}$=4.545; p=0.0148) that the Natural tree cover was greater than all Brazeau seismic line sites (0.066 > p < 0.0194). The inverse mounds at Lac La Biche did not have a significant difference in tree cover (p=0.1079), due to the high-density stem bending conducted around Inverse mounds.

Examining the percent cover data for bare peat soil on mounds, it is normal to see less than 5% soil cover on Natural hummocks, Unmounded sites and non-traditional mounds (Table 3.3). In this comparison, Inverse mounds have twelve times more exposed soil than any other type of mound. Comparing exposed soil cover among mounding methods using ANOVA indicated significant variation among treatments ($F_{5,12}$=44.173; p<0.0001), where Inverse mounds had significantly greater bare soil than all other areas (p<0.0001) and all other treatments were statistically similar (Table 3.3).

The total amount of vegetative cover and non-vegetative cover are calculated values from the nine measured community percent covers. There is a clear trend where Inverse mounds have less vegetative cover and more non-vegetative cover than any other type of mound. These values are influenced more by the amount of exposed soil than the amount of standing water. Similarly, an ANOVA analysis ($F_{5,12}$=25.134; p<0.0001), concluded that there is very strong evidence that Inverse mounds have less vegetative cover than any other type of mound (p<0.0001) while all other treatments are statistically similar (Table 3.3).

Finally, the remaining vegetative covers had little to no clear patterns observed. For lichen cover, the proportion of lichen was small across all plots, and no statistical variation was found through ANOVA analysis ($F_{5,12}$=0.697; p=0.6968). The density of forb species was consistent across all sites, and no significant differences were identified ($F_{5,12}$=0.414; p=0.8299). The amount of standing water around natural hummocks and elevated unmounded areas was very low. The mounding restoration areas saw a slight increase in standing water around mounds; however, an ANOVA analysis ($F_{5,12}$=0.767; p=0.5910) showed no evidence of significant variance.

3.3 Discussion

3.3.1 Site Microtopography

The Unmounded sections of seismic line measured at Brazeau have less variance in microtopography than expected. Current studies have shown that many years post-disturbance, many seismic lines are not regenerating high variance in microtopography (Stevenson, Filicetti & Nielsen, 2019). A previous extensive survey of 102 treed peatland seismic lines in Alberta showed that microtopography was reduced by an average of 20% compared to natural stands (Stevenson, Filicetti & Nielsen, 2019). In my study, the average height of natural hummocks was 20 cm, and the Unmounded sections of seismic line had high spots with an average height of 14.5 cm. This amounts to a 27.5% simplification in microtopography, a much greater simplification than expected. This increased simplification may be caused by further compression from heavy machinery traffic during mounding in spring 2019. At the Brazeau site, we can extrapolate that the microtopography was heavily impacted by the seismic line and 40 years later there is little to no evidence of any hummock formation. This further supports the theory that seismic line structure is inhibiting the formation of hummocks and hollows in peatlands (Pinzon, Dabros, & Hoffman, 2022).

All mounds show evidence of subsidence; however, Inverse mounds have over ten times more height loss than non-traditional mounds. To reduce the impacts of simplification from seismic lines, mounding restoration activities strive to increase microtopographical variance by mechanically creating hummocks, or mounds (Lieffers, Caners, & Ge, 2017). Non-traditional mounds were built to mimic naturally formed hummocks and had an average height of 20 cm within one season of mounding. Two years post-mounding, these mounds are now an average of 18 cm tall, showing a 10% decrease in overall height. Inverse mounds were built to be higher than natural hummocks and had an estimated 70% decrease in mound height. The reason behind this subsidence is likely the erosion of exposed soils, exacerbated by the loss of surface vegetation and accompanying rooting structures. Water is the primary cause of erosion. Based on the historic precipitation discussed in Chapter 2, we know that Brazeau had two years of extreme precipitation while Lac La Biche had one extreme and one moderate year. An important clarification is that the shared year of extreme overall precipitation was the year of mounding. The mounds were made in early spring while the ground was frozen and were planted in mid- to late-summer. For mounds that had soil exposed during mounding, there would have been little to no vegetation recovery prior to spring rain events. This series of events would have exacerbated erosion of exposed soil. A drier summer directly after mounding could have benefitted these mounds and reduced overall erosion. A contributing factor to the rate of erosion is the loss of surface vegetation and rooting structures as plant roots hold the surrounding soil in place and help the soil maintain its structure. In addition to vascular plants, mosses play an important role in mitigating erosion as they form a blanket to cover soil, intercept raindrops and retain water at a higher elevation, thereby reducing the volume of water flowing on the soil (Silva et al., 2019). However, these benefits are most apparent when moss densities are high. Silva et al.'s (2019) study identified that a moss density of 67% significantly decreased soil erosion in highly disturbed peatlands. Inverse mounds had no surface vegetation post-mounding while non-traditional mounds kept their surface vegetation, further supporting the hypothesis that Inverse mounds would erode at a greater rate. Inverse mounds are purposefully created to bury existing vegetation and expose bare soil to provide a non-competitive environment for new tree seedlings to grow (Kleinke et al., 2022). However, these conditions increase the erodibility of the mound, causing extreme soil subsidence. Inverse mounds were built much taller than non-traditional mounds but mostly subsided two years post-mounding, resulting in a mound height that is not significantly higher than non-traditional mounds. As mound height is regarded as an important characteristic to keep tree seedlings far from the water table, the construction of Inverse mounds is counter productive as it disturbs soil at a much greater depth, but this depth is not reflected in the overall mound height.

A tall mound should provide a drier environment for tree seedlings as they are farther from the water table. However, the overall height of the mound does not matter if the tree is not planted near the top of the mound. In Natural areas, trees were growing within 5 cm from the top of the mound. This distance is similar on non-traditional mounds. On Inverse mounds, trees were planted on average 12 cm from the top of the mound. Even though Inverse mounds are taller than non-traditional mounds, their trees are planted at a lower elevation. Therefore, Inverse mounds are not effectively distancing tree seedlings from the water table. Tree seedlings were planted manually on the top of each mound. There is likely some human error or poor planting that resulted in seedlings being lower than the peak. However, the pattern observed on Inverse mounds is more likely the result of mass wasting where the mound was eroded and slumping that carried soil and the tree seedling to a lower elevation. This also resulted in the mound flattening and widening to cover a greater area on the seismic line. Overall, Inverse mounds create more disturbance on the line but do not provide additional benefits to tree seedlings in terms of elevating them above the flat seismic line surface.

3.3.2 Variances in Soil Moisture

The flat areas of the seismic lines are significantly wetter than flat areas measured off the line. In addition, all mound types had consistently wetter soil than naturally formed hummocks. Many previous studies have reported that seismic lines are wetter than undisturbed areas; this is largely because the creation of seismic lines compresses the soil, causing lines to be at a lower elevation (Deane et al., 2020). Stevenson, Filicetti and Nielsen's (2019) survey found that, on average, seismic lines were 8 cm lower than undisturbed areas. The compression to the peat is a supporting factor in water retention on seismic lines. It is well known that compressed peat has a lower hydraulic conductivity which increases water retention of soil and keeps the surface wetter (Päivänen, 1973). Other studies at the Brazeau site have identified increases in soil bulk density on the seismic line, further confirming that these soils are heavily compressed (Kleinke et al., 2022).

Bulk density also increases in soil from a greater depth as the soil is naturally compressed by gravity (Deane et al., 2020). Inverse mounds have been found to have much higher bulk density than non-traditional mounds, which is likely because of general seismic line compression and natural compression of deep peat (Kleinke et al., 2022). Since bulk density is negatively correlated with hydraulic conductivity, seismic line mounds are expected to have greater water retention than natural mounds (Kleinke et al., 2022). This correlation between seismic line soils and water retention holds true in this study, as Inverse mounds were consistently wetter than non-traditional mounds and all seismic line mounds were wetter than Natural comparisons.

As compression of peat increases the water retention of mound soils, the height of the mound may not accurately represent the ability of mounds to reduce soil moisture. Overall, the soil moisture at the base of the tree seedling may be a better judge of mound effectiveness than the mound height. The measurement of soil moisture at each tree seedling found that Inverse trees were growing in significantly wetter soil than any other planting treatment. The peak of an Inverse mound is composed of peat soil from 1 m below the surface of the seismic line. Therefore, the topsoil is more compressed than an upright mound like Inline, or Hummock

Transfer mounds. The mass wasting observed on Inverse mounds also affects soil moisture near the tree, as mound slumping moves seedlings farther from the mound peak. Finally, the lack of vegetative cover means that there is no plant uptake of water. Altogether, this is leading to very wet Inverse mounds that do not mimic natural peatland soil moisture conditions.

3.3.3. Competition and Cooperation with Vegetation Communities

Having full vegetative cover on mounds provides a variety of benefits to the soil and the newly planted tree seedling. Peatland vegetation is also slow growing so the removal of vegetation in peatlands takes longer to restore than other ecosystem types (Finnegan, MacNearney, & Pigeon, 2018). As mentioned earlier, keeping existing vegetation on mounds will reduce soil erosion as roots keep soil in place, but roots also play a role in breaking up the soil, reducing soil compaction and creating drainage pathways (Nawaz, Bourrié & Trolard, 2013; Dabros, Pyper & Castilla, 2018). In direct benefit to the tree seedling, full vegetative cover will provide protection from temperature extremes, suppress weed growth and retain moderate soil moisture (Urbina, Benavides, 2015). There are also long-term benefits to vegetative cover that may be reduced or delayed if vegetation is removed, such as the cultivation of diverse mycorrhizal associations, carbon sequestration and nutrient cycling (Hobbie & Högberg, 2012). The downsides of keeping full vegetative cover on mounds is the concern they might outcompete newly planted seedlings. However, not every type of plant is a direct competitor to conifer trees. Competition for sunlight is a concern for conifer trees when plants like deciduous trees and shrubs grow faster and can shade the seedling (Finnegan, MacNearney, & Pigeon, 2018). Competition for nutrients is a concern with weeds, invasive species, and grasses in peatlands as these species grow aggressively and can easily overtake new vegetation (Urbina & Benavides, 2015). When peatlands are highly disturbed, there are opportunities for these vegetation groups to outcompete native vegetation thereby altering the vegetation composition and possibly causing the ecosite type to change (Echiverri et al, 2020). On seismic lines, which have an open canopy, the competition for light is less of a concern than it is in a mature forest. The increase in graminoids, including grasses, may be more impactful in seismic line restoration as the mechanical disturbances provide opportunities for graminoid encroachment and both Brazeau and Lac La Biche seismic lines saw greater graminoid presence compared with undisturbed areas. Overall, dense shrub and graminoid cover may restrict tree seedling growth but full vegetative cover of diverse plants should not be considered a negative characteristic of mounds.

This is especially true when the majority of vegetative cover is composed of bryophytes as seen in both Brazeau and LLB's undisturbed areas. Mosses grow cooperatively with vascular plants to create ideal microhabitats and encourage moss growth and hummock formation in peatlands (Pouliot et al., 2011). This in turn, creates ideal hummocks for tree establishment creating a cycle of positive reinforcement.

Each treatment had between 30–40% combined cover of graminoids, forbs and shrubs, highlighting the diversity of plant classes. As shown in Table 3.3, most vascular plant classes had low to moderate density. The greatest densities of graminoids were seen in Unmounded and Inverse areas with over 20% density on mounds. As graminoids are known competitors for space and nutrients, mounds with higher-than-average graminoid density may be at risk for competition. For example, Inverse mounds had the highest maximum covers of graminoids and the highest number of mounds with cover over 30%. While graminoid cover averages 20% on Inverse mounds, Sphagnum and other mosses amount to only 12%. This is a noticeably low cover compared to all other seismic lines sites and demonstrates the poor regrowth of mosses on Inverse mounds. This delayed recovery started with the original burying of moss during the mounding process. As mass wasting and subsidence buries surrounding vegetation and acts as a continuous source of soil disturbance there are fewer nearby moss groupings to expand vegetatively onto the mound peaks even though there are ample mosses to revegetate mounds through moss spores.

Recently, Echiverri et al. (2020) noted a lack of bryophyte recovery on Inverse mounds as mounds showed significantly less cover than unmounded seismic lines and undisturbed areas. In this study, the prolonged desiccation of bryophytes was the primary factor delaying recovery (Echiverri et al., 2020). The desiccation of mosses would occur if Inverse mounds were found to be significantly drier than natural or unmounded sites; however, this was not observed at the LLB sites. Inverse mounds were actually found to be wetter than undisturbed hummocks and would likely not cause prolonged desiccation of mosses. Non-traditional mounds with surviving bryophytes did not show evidence of desiccation either. Echiverri et al.'s (2022) study followed these conclusions and identified greater bryophyte recovery in flooded areas of seismic lines. My study contradicts these conclusions as the wettest mounds with an average soil moisture of 66% VWC had a bryophyte cover of 2% while the driest site with 46% VWC had a bryophyte cover of 21%. The flooded Inverse mounds had a greater cover of graminoid species than bryophytes, while seismic lines without flooding saw the greatest bryophyte recovery. There are many connecting factors delaying the recovery of bryophytes on Inverse mounds some of which may be regional or seasonal. Overall, the delay in bryophyte recovery further delays the productivity of carbon sequestration in peatlands post-disturbance (Echiverri et al., 2020). The recovery of bryophytes is a point of concern in returning ecosystem function and integrity. If bryophyte recovery is a goal in seismic restoration, non-traditional mounds or unmounded planting should be considered over Inverse mounds.

3.4 Conclusion

Overall, Inverse mounds were the only mound type to be significantly taller than Unmounded seismic lines. However, there was a surprisingly high percentage of subsidence on Inverse mounds that made them much smaller over time. This subsidence was disadvantageous to Inverse mounds as the tree seedlings were no longer planted on the tops of the mounds, thereby eliminating any height advantage of Inverse mounds. In the end, tree seedlings were planted at a higher elevation on non-traditional mounds and Unmounded areas than Inverse. In terms of the hypotheses, I confirmed that Inverse mounds are taller than Unmounded seismic lines, but non-traditional mounds are not significantly different from either Inverse or Unmounded areas. Therefore, there is no mound height advantage to any type of mound.

The soil moisture variables clearly concluded that Inverse mounds are ineffective at reducing line soil moisture. All non-traditional mounds and Unmounded areas had definite improvements in soil moisture compared to the line soil moisture, but Inverse mounds only had small reductions in soil moisture. In terms of the hypothesis, Hummock Transfer mounds had one of the lowest soil moisture averages, but they were not significantly drier than any other non-traditional mound. Therefore, the strongest pattern observed is that Inverse mounds are not an effective restoration strategy to decrease soil moisture on peatland seismic lines.

The key pattern observed in vegetation communities was that Inverse mounds had the lowest bryophyte cover and overall plant cover, which is attributed to the increased level of disturbance in creating these mounds. Bryophyte cover is known to return slowly on seismic lines and the Unmounded areas that were not disturbed in 2019, had an almost full cover of bryophytes. Examining the initial hypotheses, I did not see an increased density of shrubs on

Hummock Transfer mounds. The expectation that a high density of shrubs would be transplanted with the hummock was incorrect. Unmounded and Inverse mounds had high densities of graminoid cover. Therefore, non-traditional mounds seem to be able to mitigate graminoid encroachment while Inverse mounds are more susceptible.

In conclusion, out of all mound types, Inverse mounds were the least efficient at recreating natural hummock conditions. While they are technically taller, the expected benefits of the soil profile, soil moisture and high vegetation diversity are not being displayed. The other mound types of Rip and Lift, Hummock Transfer and Inline Mounding are relatively equal in height, soil moisture and vegetation composition.

Chapter 4: Impacts of mounding on planted black spruce seedling growth

4.1 Introduction

The goal of this chapter is to identify how black spruce growth rates differ across mounding methods and investigate the supporting and limiting factors of seedling growth. Four datasets were used in this chapter: 1) To identify seedling condition, a dataset of all unfertilized black spruce was used (n = 725); 2) To identify seedling growth rates across treatments, a dataset of all living, unfertilized black spruce was used (n = 699). To investigate how characteristics of the surrounding microenvironment affect seedling growth rates using a linear mixed effect model (LME) a dataset of all living, unfertilized black spruce planted on a seismic line was used. The first LME model included 3) all above-characteristics (n = 633) and the second LME model included 4) only the black spruce removed from the line for further below-ground observations in the laboratory (n = 50).

This chapter aims to answer the following research questions:

1. What patterns can be observed in black spruce survival across mounding treatments? What patterns can be observed in the rates of death or damage to the seedlings?
2. How do black spruce growth rates change over time and across mounding treatment type?
3. What characteristics best explain variance in black spruce growth rates? How do these characteristics interact with each other and directly affect seedlings? Are these characteristics more prevalent on any specific mounding treatment type?

Seedling condition was observed in the field using a standardized methodology (Chapter 2). The hypotheses related to seedling condition are that Unmounded and Inverse seedlings would have the highest rates of death among black spruce while Hummock Transfer mounds would have the best overall seedling condition. Many previous studies have identified that mounding decreases soil moisture on seismic lines and increases seedling growth (Pinzon, Dabros & Hoffman, 2022). From this information, I extrapolated that Unmounded areas would have higher rates of seedling death due to their unfavourably wet soil profile. Echiverri, Macdonald, and Nielsen’s (2022) recent study observed that Inverse mounding creates large open pools of water and has slow vegetation recovery. These conditions may lead to an instability of the mound's soil profile leading to erosion and bringing the seedling closer to the water table, resulting in higher rates of death. In direct opposition with Inverse mounds, the naturally developed hummocks' structured soil profile and dense existing vegetation of Hummock Transfer mounds led me to predict that they would best support healthy black spruce seedlings.

Seedling growth was measured as the length of the seedlings first leader length (2021's growth) and second leader length (2020's growth) and added to calculate biennial growth. The hypothesis for seedling growth was that non-traditional mounds would promote better growth rates in black spruce seedlings, as all non-traditional mounds create an elevated dry space for seedlings and all have upright soil profiles. Other studies show that an inverted soil profile increases bulk density, inhibits vegetation regrowth, and lowers substrate quality (Kleinke et al., 2022). Altogether, these factors suggest that Inverse mounds may also inhibit growth in planted black spruce seedlings.

The LME models were run with 37 unique characteristics, encompassing mound elevation (n = 3), soil moisture (n =8), vegetation communities (n = 10), line characteristics (n = 7) and root characteristics (n = 9). The hypothesis associated with the LME models are that mound height and mound soil moisture characteristics would consistently be strong predictors for black spruce seedling growth. Studies reporting the benefits of high and dry mounds are common in the field of seismic line restoration (Davidson et al., 2020). ECM presence is also thought to be an important variable to explain variance in seedling growth. ECM forms mutualistic relationships with tree roots to improve nutrient and water uptake, thereby supporting seedling growth (Mäkipää et al., 2023). However, it is expected that ECM presence would be negatively correlated with growth and be more prevalent on slow-growing seedlings that require additional assistance in the uptake of nutrients. At this stage in initial seedling survival, the benefits of ECM may not yet be reflected in seedling leader length.

4.2 Results

4.2.1 Black Spruce seedling survivability

In Natural undisturbed areas, seedling health was very good. No dead Black Spruce trees were observed and 90% of Natural trees were classified as 'Healthy', which is characterized by green needles with no evidence of browsing or damage. No seismic line site reached the level of healthy conditions seen in the undisturbed regions. Unmounded areas of seismic lines had the fewest ‘Healthy’ trees at only 43% of seedlings, while the number of ‘Unhealthy’ trees had a similar proportion (36%). The Unmounded areas had no seedlings classified under ‘Dieback with regrowth’; however, this treatment had the highest proportion of ‘Dieback’ seedlings (13%). This treatment also had the highest proportion of ‘Dead’ seedlings at 8%. Looking into the survival rate of Black Spruce seedlings planted in Unmounded regions and the number observed, the estimated survival rate is between 63% to 73% (Appendix A). Overall, the Unmounded areas of seismic line showed greater degradation in seedling condition than any other treatment. Rip and Lift and Hummock Transfer treatments were the most similar in terms of black spruce conditions. Both had over 50% ‘Healthy’ seedlings, ~30% ‘Unhealthy’ seedlings and a small number of other conditions. The greatest difference was that Hummock Transfer treatments had twice as much tree mortality, making it the second highest mortality rate. The overall survival rates were similar with 85% survival for Rip and Lift and a range of 64% to 84% for Hummock Transfer (Appendix A). This demonstrated that Black Spruce seedlings planted on Rip and Lift mounds, have the highest survival rates of all studied mounding treatment.

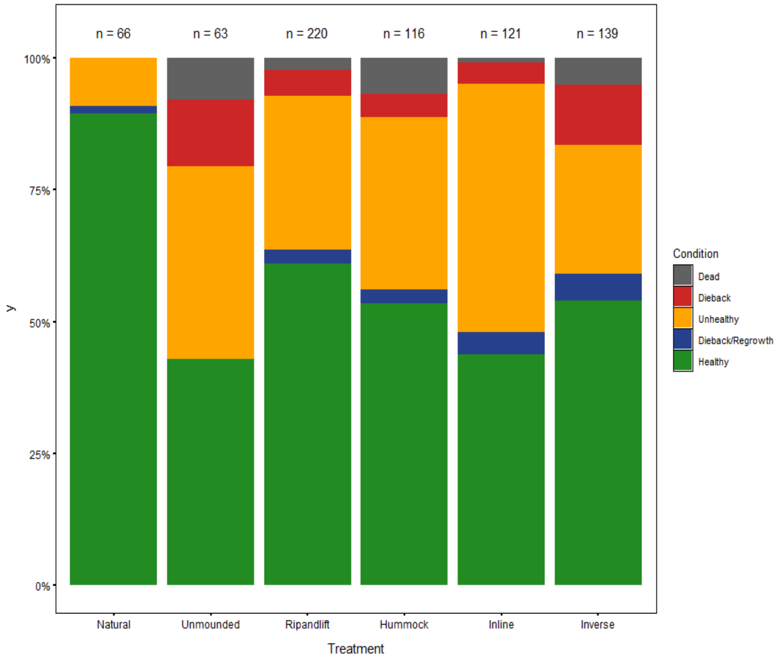

Figure 4.1: Percent proportion of Black Spruce seedling health condition by mounding method.

Inline Mounding treatments stand out with the highest proportion of 'Unhealthy' seedlings (47%). However, due to the lack of other condition categories there are still many 'Healthy' seedlings (43%). This treatment is also the only one to have more Unhealthy than Healthy seedlings, which creates a pattern similar to the Unmounded sites (Figure 4.1). The overall survival rate, however, was in the same ranges as all non-traditional mounding methods (67% - 87%; Appendix A). The low mortality of seedlings is also supported by Inline mounds having the lowest proportion of 'Dead' seedlings (1%). Inverse mounds had the lowest proportion of 'Unhealthy' seedlings than any other seismic line site. Yet, they had the highest proportion of damaged seedlings with high 'Dieback' and 'Dieback with regrowth' classifications (16%). The proportion of 'Healthy' and 'Dead' seedlings were average compared to other seismic line sites. Overall, among the treatment sites, Unmounded areas had the poorest seedling conditions while Rip and Lift mounds had the best conditions. Hummock Transfer, Inline Mounding and Inverse Mounding had similar seedling conditions.

4.2.2 Black Spruce seedling growth

The growth of natural and planted seedling was determined by the first and second leader length, which are consolidated to calculate the biennial growth from 2020 to 2021. In 2020, the planted seedlings had their first full growing season. Natural trees had a larger growth year in 2020 (average = 7 cm) than in 2021 (4 cm; Figure 4.2). Biennially, Natural trees had lower growth rates than any of the seismic lines sites with an average of 11 cm. Unmounded seedlings had an average growing year in 2020 with an average of 8 cm. These sites had a below-average season in 2021 with only approximately 3 cm of growth, making this the lowest rate of growth of any planted seedling treatment. Biennially, Unmounded seedling growth was slightly below average, when compared to all other sites. Rip and Lift seedlings had a high growth in rate in 2020 (10 cm) and a moderate rate of growth in 2021 (4 cm). Rip and Lift seedling growth rates share many similarities with Hummock Transfer treatments. Hummock Transfer seedlings had the highest rate of growth in 2020 at just over 10 cm of average growth. The interquartile range started at the highest value of Q1 = 8 cm and reached a similar value as the Unmounded seedling distribution with Q3 = 12 cm. In 2021, Hummock Transfer had an average growth of only 3.5 cm. Biennially, Rip and Lift and Hummock Transfer mounding methods had the highest rates of growth with an average around 14 cm. Inline Mounding seedlings had an average rate of growth in 2020 (9 cm) and 2021 (4.5 cm). With a normal distribution, Inline Mounding growth rates were consistent and slightly below average when compared to other non-traditional mounding treatments (Figure 4.2).

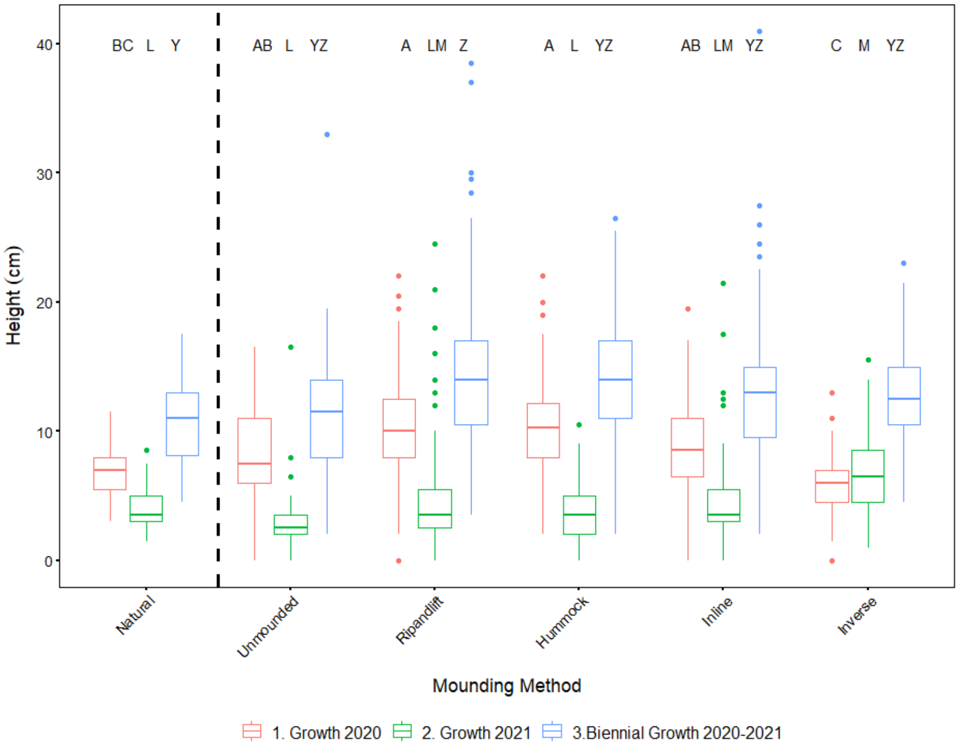

Figure 4.2: Second leader length in (cm) to determine 2020 annual growth, first leader length in (cm) to determine 2021 annual growth and calculated biennial (2020-2021) growth by mounding method. Significant differences displayed above in letter notation where treatments are significantly different if they do not have any letters in common. Letters are to be compared only within one growth time period.

Black Spruce seedlings planted on Inverse mounds saw the least amount of growth in 2020 compared to all other treatments with an average of only 6 cm. In 2021, Inverse seedlings had the highest average rate of growth (7 cm), and this was the only treatment to have more growth in 2021 than the previous year. It should be noted that Inverse seedlings were measured at the LLB study site while other mounding treatments were all measured at Brazeau and interannual patterns of weather did vary between the sites (Chapter 2). With an average growth rate of 13 cm, Inverse seedlings had the lowest biennial values of all other seismic line sites. Overall, there is a consistent pattern where Black Spruce trees had more growth in 2020 than in 2021. This pattern is only broken by Inverse seedlings, who had similar average growth rates over both years with a slightly higher interquartile range in 2021.

Growth in 2020 was significantly different between treatments (ANOVA, $F_{4,9}$=12.680; p=0.0002), with pairwise comparisons providing strong evidence that Hummock Transfer (p=0.0018) and Rip and Lift (p=0.0027) treatments had significantly more growth in 2020 than Inverse mounds. There was moderate evidence that Inline Mounding growth in 2020 was greater than Inverse (p=0.0296) and weak evidence supporting that Unmounded seedlings had more growth than Inverse in 2020 (p=0.0744). In terms of 2021 annual seedling growth, treatments also varied significantly (ANOVA, $F_{4,9}$=4.049; p=0.0219) with moderate evidence that Inverse seedlings grew more than Unmounded seedlings (p=0.0200). Furthermore, weak evidence supported that Inverse seedlings also grew more than Hummock Transfer seedlings (p=0.0516). While varying patterns were observed between treatments for 2020 and 2021 growth rates, when combined over the two years, only Rip and Lift and Natural treatments showed differences in biennial growth (p=0.0520). In this case, weak evidence indicates that Rip and Lift treatments had higher growth rates than Natural trees (ANOVA, $F_{4,9}$=3.147; p=0.0482; Figure 4.2).

4.2.3 Above-ground characteristics supporting black spruce seedling growth

A linear mixed effects model with backwards stepwise elimination was used to isolate the effects that are the most likely to explain variance within the response variable (black spruce growth) of the dataset (see Chapter 2 for statistical methods). The response variables used in this project are all measures of seedling growth, so all the effects listed in Table 4.1 are likely to explain change in seedling growth.

Looking at the annual growth in 2020, the percent cover of Sphagnum moss, shrubs and other trees, as well as the height that the tree seedling is planted, explain variance within the dataset. Based on the p-values the percent cover of Sphagnum moss (p<0.0001) is more likely to explain variance within the dataset than any other effect. Looking at the ‘Value’ of each effect we can understand the correlation of the response variable and the effect on a scale from 1 to -1. All four effects have a weak positive correlation, meaning that increases in these factors would support seedling growth. The ‘Marginal R^2’ value demonstrates the percentage of variance being explained by the model. In this model, only 9.6% of variance is explained which suggests that key effects on black spruce seedling growth, not measured in the present study, are missing from the model.

In 2021, the effects on seedling growth were similar with two vegetation cover effects, one mound height effect and a new identified effect of soil moisture at the seedling. Within this model, the percent cover of shrubs (p=0.0028), the height of the mound (p=0.0018) and the soil moisture (p=0.0004) were the most likely to impact growth. Soil moisture at the seedling provides the strongest evidence of a relationship to growth within the model. All four effects have a weak correlation and while shrub cover and mound height are positively correlated, moss cover and soil moisture are negatively correlated. As with 2020 growth, only a small amount of variance (8.1%) was explained within this model.

Table 4.1 Results of linear mixed effects model of environmental parameters for unfertilized black spruce seedling growth from 2020 to 2021. Only significant parameters and interactions are shown.

Model Response Variable	Effect	Value	F	p-value	Marginal R^2	Conditional R^2
Annual Growth 2020	INTERCEPT	7.384	$F_{1,615} = 370.37$	<0.0001	0.096	N/A
	PC Sphagnum	0.020	$F_{1,615} = 16.75$	<0.0001		
	PC Shrubs	0.024	$F_{1,615} = 3.12$	0.0779		
	PC Tree	0.074	$F_{1,615} = 2.97$	0.0854		
	Height of Planting	0.022	$F_{1,615} = 3.00$	0.0835		
Annual Growth 2021	INTERCEPT	4.320	$F_{1,615} = 81.08$	<0.0001	0.081	N/A
	PC Moss	-0.010	$F_{1,615} = 3.01$	0.0830		
	PC Shrubs	0.029	$F_{1,615} = 8.98$	0.0028		
	Height of Mound	0.034	$F_{1,615} = 9.80$	0.0018		
	Soil Moisture at Tree	-0.022	$F_{1,615} = 12.66$	0.0004		
Biennial Growth 2020-2021	INTERCEPT	12.042	$F_{1,613} = 554.08$	<0.0001	0.088	N/A
	PC Sphagnum	0.015	$F_{1,613} = 4.15$	0.0420		
	PC Moss	-0.011	$F_{1,613} = 6.70$	0.0099		
	PC Shrubs	0.048	$F_{1,613} = 4.96$	0.0263		
	PC Tree	0.109	$F_{1,613} = 3.52$	0.0612		
	Height of the Mound	0.043	$F_{1,613} = 3.32$	0.0689		
	Soil Moisture at Tree	-0.019	$F_{1,613} = 7.23$	0.0074		

The LME model results for biennial growth gave similar results to the individual annual models (Table 4.1). The effects with the greatest evidence of significance are the percent cover of moss (p=0.0099) and the soil moisture at the seedling (p=0.0074). The direction of correlation remained the same for each effect as in previous models. One notable change in correlation is with the percent cover of trees whose correlation coefficient became much stronger (R = 0.109), indicating a stronger linear positive relationship with biennial growth. Similar to the annual models, this model also explains only a small fraction of variance in biennial growth (8.8%).

Overall, Black Spruce seedlings planted on the seismic line are most likely to grow taller when there is a moderate cover of Sphagnum moss, shrubs and other tree species but not a high percentage cover of other mosses. The seedling growth is also supported when they are planted high up on tall mounds and the soil moisture near the seedling is low.

4.2.4 Below-ground characteristics supporting black spruce seedling growth

A subset of the planted black spruce seedlings was removed for further study on their below-ground properties such as biomass, root structure and ectomycorrhizal associations in the laboratory (Chapter 2). The observations of ECM associations (Table 4.2) indicate that Inverse seedlings had the greatest proportion of interaction with ECM, by total seedling count and average root mass colonization. Non-traditional mounds had the next greatest proportions of ECM associations followed by Unmounded and Natural sites. However, further statistical analysis indicated that there is no statistical difference in ECM associations across mounding methods (ANOVA, $F_{4,8}$=0.825; p=0.5446).

Table 4.2 Summary of ECM observations of unfertilized black spruce roots by mounding method.

	Natural	Unmounded	Rip and Lift	Hummock Transfer	Inline	Inverse
Seedlings with oberved ECM presence	42%	50%	67%	55%	56%	75%
Average root colonization of ECM	5.4%	3.7%	6.4%	6.2%	4.4%	8.3%

Results from the ECM analysis were included in LME models using a dataset of the unfertilized black spruce seedlings that were removed from the peatland for further study in the laboratory. When these variables were included in a linear mixed effects model, I observed different patterns of effects and correlation to response variables of seedling growth (Table 4.3).

Examining the seedling growth in 2020, the LME identified the width of the seismic line (p=0.0802), the total cover of living vegetation (p=0.0077) and the difference in soil moisture between the tree and the peak of the mound (p=0.0832), to be the most likely explanations for variance within the dataset. These three effects were not identified in the previous LME model that excluded laboratory variables. Line width has a strong negative correlation with 2020's annual seedling growth (R=-0.613), this indicates that narrower sections of seismic line had greater rates of growth. These variables explain about one quarter of total variance within the 2020 annual growth model (marginal R^2 = 22.8%). Although the laboratory variables (i.e., above- and below-ground biomass, root ball size, root branching order, stem diameter and percent ECM associations) were included in this model, none of these effects remained as significant variables in the model after the stepwise elimination process.

Table 4.3 Results of linear mixed effects model of environmental and laboratory parameters for unfertilized black spruce seedling growth from 2020 to 2021. Only significant parameters and interactions are shown.

Model Response Variable	Effect	Value	F	p-value	Marginal R^2	Conditional R^2
Annual Growth 2020	INTERCEPT	8.182	$F_{1,34}$ = 472.89	<0.0001	0.228	0.228
	Line Width	-0.613	$F_{1,34}$ = 3.25	0.0802		
	Total Vegetation Percent Cover	0.044	$F_{1,34}$ = 8.03	0.0077		
	Difference in Tree to Peak Soil Moisture	0.028	$F_{1,34}$ = 3.19	0.0832		
Annual Growth 2021	INTERCEPT	3.894	$F_{1,30}$ = 50.39	<0.0001	0.671	N/A
	PC Sphagnum	0.008	$F_{1,30}$ = 5.00	0.0330		
	PC Lichen	0.390	$F_{1,30}$ = 18.54	0.0002		
	PC Shrubs	0.056	$F_{1,30}$ = 4.71	0.0381		
	PC Water	-0.087	$F_{1,30}$ = 11.49	0.0020		
	Soil Moisture at Tree	0.005	$F_{1,30}$ = 5.98	0.0205		
	Below-Ground Biomass	-0.105	$F_{1,30}$ = 4.69	0.0384		
	%Ectomycorrhizal Presence	-0.070	$F_{1,30}$ = 11.31	0.0021		
Biennial Growth 2020-2021	INTERCEPT	13.854	$F_{1,35}$ = 855.38	<0.0001	0.172	0.172
	PC Lichen	0.750	$F_{1,35}$ = 6.61	0.0145		
	Below-ground Biomass	-0.301	$F_{1,35}$ = 3.54	0.0683		

During the 2021 growing season, many variables were identified as key effects towards the response variable. These effects included vegetation characteristics, soil moisture characteristics and root structure characteristics. The percent cover of lichen species had a moderate positive correlation to seedling growth (R=0.39) and suggests that the presence of lichen is associated with ideal growing conditions. This effect was also the most likely out of all original variables to explain variance of seedling growth in 2021 within the dataset (p=0.0002). The cover of standing water was also a newly introduced effect with a weak negative correlation. The percent cover of Sphagnum and shrubs, and the soil moisture at the seedling have similar correlation relationships to seedling growth as the previous LME model that excluded laboratory variables. This model also introduces two root characteristics as key effects to explain seedling growth patterns. The below-ground biomass had a moderate negative correlation with growth (R=-0.105), suggesting moderate evidence that seedlings with less developed root systems are growing taller. The presence of ectomycorrhizal associations in the root mass of planted seedlings was also a significant effect to explain growth variance (p=0.0021). This factor has a weak negative correlation to 2021 seedling growth in the LME model (R=-0.07) but has a moderate positive correlation to below-ground biomass (R=0.25). This relationship suggests that together, a low root biomass and low ectomycorrhizal association should be characteristic of taller black spruce seedlings. Overall, these seven effects explain 67.1% of 2021 annual seedling growth in this LME model.

The final LME model in Table 4.3 examines the response variables of biennial growth and identifies two repeat effects of the percent cover of lichen (p=0.0145) and the below-ground biomass (p=0.0683) of the black spruce samples. In this model, the percent cover of lichen had a strong positive correlation to growth (R=0.75), enforcing the conclusion that the nearby presence of lichen is correlated to tree growth. Root biomass was still negatively correlated to seedling growth (R=-0.301). As repeated effects in the black spruce dataset with included laboratory variables, both lichen cover and root biomass have stronger correlations to the response variable, but have lower p-values, making them less likely to contribute to the explanation of variance of biennial growth. The marginal R^2 value was 17.2%, much less than the 2021 LME model. This suggests that these two effects alone cannot explain the majority of variance within the model.

Overall, based on the LME models, black spruce seedlings planted on narrow seismic lines, with dry soil conditions and a high proportional cover of Sphagnum, lichen and shrubs will grow the best. Additionally, results suggest that taller seedlings concentrate their growth above-ground and do not focus their available energy on developing their below-ground biomass or ectomycorrhizal associations.

4.3 Discussion

4.3.1 Trends in black spruce seedling growth and condition

Biennially, there are clear trends in seedling growth. All seedlings at the Brazeau site had high growth rates in 2020 and low growth rates in 2021. This trend is opposite at the Lac La Biche sites where 2021's growth was slightly greater than the previous year. These differences are likely due to changes in location and climate. For example, the Lac La Biche site is farther north than Brazeau which might impact the length of the growing season or growth productivity. In terms of precipitation events, both sites had a wet year in 2019 and 2020 and a dry year in 2021. The high levels of precipitation may have positively impacted seedlings at Brazeau but negatively impacted those planted on Inverse mounds. Likewise, Inverse seedlings may have reacted more positively to the dry year in 2021. To clearly identify the root cause behind these patterns of growth, further study is necessary involving Inverse and non-traditional mounds on the same study site. A broader study could also help determine growth patterns of black spruce seedlings if multiple areas of Inverse and non-traditional mounds were examined across Alberta. Within this study, the biennial growth from 2020-2021 will act as the best measure of overall seedling growth.

Seedlings planted on Rip and Lift had the best overall seedling growth and health conditions. These seedlings had low mortality, fewer unhealthy seedlings, above average rates of growth and a strong 83% survival rate. Rip and Lift seedlings were also the only treatment to show a significantly higher biennial growth rate than Natural trees. While they were not growing significantly faster than any other planting treatment, this indicates that Rip and Lift seedlings are showing a slight advantage in survival. Altogether, this information supports Rip and Lift as the best mound type to support the initial survival of black spruce seedlings. The smaller footprint of disturbance created by Rip and Lift mounds is another benefit of this treatment type, as we can expect fewer emissions of GHGs, and a faster recovery time of the peatland's ecosystem services (Echiverri, Macdonald & Nielsen, 2022). Using overall growth and seedling condition as a measure, Hummock Transfer seedlings had the next best survival average, followed by Inline Mounding, Unmounded, and Inverse Mounding.

Hummock Transfer and Inverse seedlings had high mortality rates that can be attributed to the high moisture content on the line. Many areas of Hummock Transfer and Inverse treatment plots were partially flooded at the time of sampling. This is reflected by the percent cover of standing water identified around each tree (Table 3.3, Chapter 3). It is likely that high cover of standing water around the black spruce seedlings will negatively affect growth and health since the seedling roots will not grow deeply and may only cover a small area within the hummock or mound (Lieffers & Macdonald, 1990). These two treatment types may be more likely to have nearby standing water based on the way they are constructed. Hummock Transfer mounds are transplanted onto the seismic line in the spring prior to the thawing of the ground. This means it is difficult to determine if the hummocks are being placed in areas prone to pooling and since the seismic line soils are not being disturbed on the line, it is more likely that these areas will continue to gather standing water and could negatively affect the seedlings during times of high precipitation (Morris et al., 2009). Morris et al.'s (2009) study of soil rutting in peatlands also provides evidence of the negative impacts of pools of standing water on black spruce seedlings. For Inverse mounds, the large holes dug onto the line left open areas for water to gather, leading to large open pools of standing water directly beside the tree seedling. Many seedlings were either planted low on the mound or had shifted very close to these open pools. This, in addition to the high mound soil moisture content observed on Inverse lines, would negatively affect the growth of black spruce seedlings.

4.3.2 Black spruce seedling growth patterns on Inverse mounds

Inverse seedlings had the lowest biennial growth rate by a small margin. However, they had significantly less growth in 2020 than all other treatment types and were only significantly greater than Unmounded seedlings in 2021. Inverse seedlings also had very high proportions of damage to the seedlings and a moderately high proportion of seedling mortality. Altogether, these conditions provide evidence that black spruce seedlings planted on Inverse mounds are struggling to effectively survive and establish themselves.

As mentioned previously, the high percent cover of standing water near seedlings on Inverse mounding sites might be negatively affecting the survival of seedlings. From field visits, I know that many of the dead seedlings were found planted in waterlogged conditions or in close proximity to an open pool of water. In addition, while the Inverse lines had slightly lower average soil moisture than the lines at Brazeau, the Inverse mounds themselves were significantly wetter than any other planting treatment. The inability of Inverse mounds to create minimally saturated soil conditions for tree seedlings negatively affects a seedling's ability to expand their roots into dry soil (Lieffers & Rothwell, 1987). In peatlands or other wetted landscapes, trees are most often found on elevated spots or hummocks since a black spruce's roots will not grow below the water table (Lieffers & Rothwell, 1987). As shown in Figure 3.1 (Chapter 3), there was a greater proportion of Inverse seedlings planted on or slightly above the flat of the seismic line. These seedlings would receive no benefit from the mounds and have trouble growing in wet conditions since seismic line soils are significantly wetter than natural peatland soil (Chapter 3) and are generally unsuitable for conifer seedling establishment (Langdon, Dovciak & Leopold, 2020).

The lack of surrounding vegetation on Inverse mounds may also contribute to their low growth rate in 2020 or their overall poor health conditions. As Inverse mounding purposefully buries the nearby vegetation on the seismic line, it can be assumed that the vegetation density after mounding in 2019 was very low, with continual improvement in 2020 and 2021. Several studies have highlighted the importance of having a moderate density and diversity of vegetation to support planted seedling growth on mounds (Lett et al., 2020; Pace et al., 2016). The LME models highlighted in Table 4.1 and Table 4.3 show that all vegetation communities, except for moss, are positively correlated with growth. In this study, moss communities are likely negatively correlated to growth because they are inversely related to Sphagnum cover and not because they affect seedlings negatively in moderate densities. Since Inverse mounds had the lowest proportions of overall vegetation cover, this provides support for the conclusion that Inverse mounds do not have the density of diversity of vegetation required to fully support seedling establishment. Overall, the LME models of unfertilized black spruce seedlings indicate that above-average vegetative cover on mounds will support successful seedling growth and establishment. The specific impacts of planting seedlings with high, moderate, or low vegetative cover have not been widely studied and these differences may further explain the poor growth rate on Inverse mounds in 2020.

4.3.3 Targeted black spruce planting on Unmounded seismic lines

While there have been many records of seismic lines struggling to revegetate with trees naturally (van Rensen et al. 2015), this study has shown that planted seedlings on unmounded seismic lines can survive two years post-planting. The majority of Unmounded seedlings were alive and growing at a similar rate as the other planted seedlings on mounded treatments. As such, there is evidence that a targeted planting approach (also called plant-as-is) may be an effective restoration technique involving no mounding and minimal soil disturbance. First of all, as identified in Chapter 3, non-traditional mounds are neither significantly taller nor drier than the high microtopography measured on the unmounded seismic line. Overall, mound height and soil moisture measurements are statistically similar between unmounded and non-traditional mounds. Most importantly, the tree growth in Unmounded areas was not significantly different from non-traditional mounds. Although there were inter-annual differences between Unmounded and Inverse mounds, statistically speaking, Unmounded areas support black spruce seedling survival as well as any other mound type. These results point towards a conclusion that planted black spruce seedlings can successfully survive on seismic lines without any MSP method. It is also noted that the Unmounded areas of Brazeau have lower than average variance in microtopography compared to the extensive survey of peatland seismic lines conducted by Stevenson, Filicetti & Nielsen (2019). If black spruce seedlings can survive on an unmounded seismic line with high microtopographical reduction (>20% reduction), there is an expectation that seedlings would have an increased rate of survival if they were planted on an unmounded seismic line with low microtopographical reduction (<20% reduction).

However, there is counterevidence that shows Unmounded seedlings are struggling to grow compared to mounding treatments. Looking directly at growth averages, it is noted that Unmounded seedlings were consistently in the lower range of growth averages. This means that, while they are not statistically different, Unmounded seedlings were often growing less well than any other treatment’s seedlings. It is also important to note the seedling conditions, Unmounded seedlings had the highest rates of ‘dead’ and ‘dieback’ conditions, further highlighting the poor health conditions of Unmounded seedlings. The slightly poorer results of Unmounded seedling condition and growth may not be statistically significant in 2021, but in the next few years we may begin to see a divide in black spruce seedling growth across mounding treatments. The limitation of this conclusion is that this study is observing seedlings two years post-planting and can only provide insight on the initial growth and survival of seedlings. These preliminary conclusions cannot be extrapolated to provide conclusions on the success of seedling survival in 5 or 10 years or conclude on their ability to reintegrate the forest canopy level. This is strictly a conclusion on the initial survival of seedlings.

Overall, restoration professionals should not discount targeted planting as an effective reforestation technique. There is evidence provided that black spruce seedlings can survive when planted strategically (i.e., on existing local high points) on unmounded seismic lines. While it is difficult to conclude on the effects to forest canopy recovery at this stage of seedling survival, future research may provide more insight on the positive or negative effects of targeted planting. This technique may prove very useful in seismic restoration efforts, especially in areas where mounding is unreasonable or not cost effective.

4.3.4 The ideal growth conditions of black spruce seedlings

As expected from our knowledge of previous mounding studies, black spruce seedlings thrived in elevated, dry conditions with moderate cover of bryophytes and woody vegetation. This is the conclusion identified from the LME model performed with a dataset of all living, unfertilized black spruce seedlings planted on a seismic line. When the below-ground effect variables were added to the LME model (Figure 4.2), the impact of mound and planting elevation was eliminated from the model. Instead, an emphasis was placed on root characteristics like total below-ground biomass and ECM associations. Soil moisture and vegetative cover remained key effects. With this second model, we can conclude that black spruce seedlings thrived on narrow dry lines with dense and diverse vegetative cover. The most successful trees did not expend much energy on developing their below-ground biomass or ECM associations.

The elevation of the tree seedling was an important effect identified in Table 4.1 for each growth rate response variable, which was an expected result given our current understanding of how trees often thrive on mounded seismic lines (Filicetti, Cody & Nielsen, 2019). However, the height of planting was highlighted as a key effect over the height of the mound in response to 2021's seedling growth. This indicates that in this case the total mound height was less important than the careful planting of seedlings. The difference between these two variables is subtle. Essentially, a tall mound has a greater potential soil volume for expansion of tree roots without interacting directly with the water table. The planting elevation is a better measure of how much potential growing space is available to the tree seedling. If tree seedlings are planted far below the mound peak, they lose immediate access to much of this potential rooting space. While tree roots can certainly grow upwards, this behaviour is not typical of conifer trees and may negatively impact the stability of tree rooting structures and the efficiency of water and nutrient uptake (Krause & Lemay, 2022). The effect variables related to soil moisture also indicate that dry conditions are ideal to support tree growth as roots cannot uptake nutrients effectively if they are in direct contact with the water table (Langdon, Dovciak & Leopold, 2020). Altogether, trees planted on tall mounds with a large rooting space, or near the top of the mound to make the most efficient use of unsaturated soil created during mounding, had greater growth rates.

When below-ground variables were added to the LME model in Table 4.2, elevation variables were no longer identified as key effects and were replaced with below-ground biomass and ECM presence. Seedlings with poor below-ground growth rates and few ECM associations had better rates of growth. These variables are highly related to the availability of rooting space for black spruce seedlings. Trees grow roots quickly when the situation demands for it, namely when the tree is not securely planted or if there is a lack of water or soil nutrients, but black spruce trees generally have shallow rooting structures (Krause & Lemay, 2022). The seedlings planted on these seismic lines already had established root balls capable of supporting tree growth, so there was no immediate need to rapidly expand the roots. Therefore, rapid root expansion is an indicator that the tree was lacking in either support, water, or soil nutrients. If trees are planted in ideal conditions, they should have a smaller below-ground biomass after only two growing seasons. ECM associations are the densest in roots with poor water and nutrient uptake, as these fungi form mutualistic relationships to provide roots with water and nutrients in exchange for plant carbohydrates (Mäkipää et al., 2023). Therefore, seedlings with many ECM associations are lacking in key nutrients which may be related to a poor microsite environment. Overall, the careful and stable planting of black spruce seedlings in areas with access to water and soil nutrients and available space for roots to grow is a major determining factor for seedling growth rate. To translate this conclusion onto what is known about the available rooting space on built mounds, Inverse mounds have the poorest ability to provide dry rooting space for seedlings.

Since Inverse mounds are prone to subsidence, they lose potential rooting space with each passing year which leads to tree roots moving closer to a direct interaction with the water table (Chapter 3). When building mounds, it is important that mounds are capable of maintaining their form for many years.

In terms of vegetative communities, Sphagnum moss, lichen and shrub cover were all consistent effects identified in LME models. Shrub cover and Sphagnum moss cover are positively correlated with tree seedling growth, which indicates that a high density of Sphagnum moss (> 60%) and a moderate density (> 15%) of shrubs and lichen (>0.3%) are beneficial to seedling growth. These conclusions are in contrast to past research which has identified shrubs as a direct competitor for sunlight and nutrients (Hébert et al., 2010). However, with a highly disturbed system like a seismic line that has an abundance of sunlight, this competition may not limit initial growth rates. Similarly, Sphagnum mosses increase the acidity of peatland soils and form dense carpets that can choke out vascular plant species and should result in a decreased growth rate for seedlings (Granath, Strengbom & Rydin, 2010). While a full coverage of either of these vegetation communities may negatively impact growth, at the densities observed on the seismic lines, there was little evidence of interspecies competition. Lichen was present on the seismic line in very small numbers, making it difficult to confidently correlate lichen presence with seedling growth. In boreal peatlands, lichen is commonly found in dry areas, it may be correlated with dry microsite conditions (Harris et al., 2018). Lichen is commonly associated with positive benefits to ecosystem biogeochemistry that can support vegetation productivity (Cornelissen et al., 2007). Further studies into the biogeochemistry of mound microsites might provide more evidence linking vegetation productivity and lichen presence in boreal peatlands.

In both sets of LME models, Sphagnum moss was positively correlated with seedling growth while other mosses were negatively correlated. On mounds, the presence of Sphagnum and other mosses are inversely related since bryophytes take up the same physical space in peatlands as the lowest ground cover vegetation. The type of bryophyte present on a mound depends on external factors like the existing bryophytes in undisturbed areas, the hydrology and acidity of the site and the availability of light (Vitt & House, 2021). Bryophyte presence can also be influenced by competitive pressures as bryophytes more suited to an environment can outcompete other species (Kangas et al., 2014). In this study, bryophyte variation across the seismic lines is likely due to species adaptation, as Sphagnum mosses are better adapted to bogs and poor fens while other mosses prefer rich fens systems with moist to dry conditions (Vitt & House, 2021). Moss presence is linked with ecosystem type, which leads to the conclusion that black spruce tree seedlings are growing faster in comparatively poorer soils than tamarack. At both Brazeau and Lac La Biche sites, Sphagnum moss was the dominant bryophyte type in the natural areas and on the seismic line. Other mosses were also present within each treatment type but there were greater average densities in the Natural area, on Unmounded areas and on Hummock Transfer mounds. As identified in Chapter 3, these regions had the lowest average mound peak soil moistures supporting the conjecture that other mosses prefer drier peatland conditions.

Another important commonality between Natural, Unmounded and Hummock Transfer mounds are their low overall mound disturbance. These three subsite locations can be considered the least disturbed since Natural or Unmounded areas were undisturbed during mounding activities and the Hummock Transfer mounds are natural hummock formations. This supports the conclusion that other mosses are slow to colonize disturbed soils, compared to Sphagnum moss. Furthermore, high percent cover of Sphagnum moss may be an indication that soils were heavily disturbed in recent years. Since Unmounded areas had a very high percent cover of other mosses and the lowest seedling growth rates, it is likely that it has skewed the data which resulted in a connection between other moss cover and low seedling growth. There is no other evidence in this study to link moss presence with poor seedling growth. The likely conclusion is that Sphagnum to other moss cover ratio is more related to the rich fen to poor fen gradient and/or timeline of bryophyte successional colonization and this combination of factors contributes to the observed patterns of seedling growth.

The greatest limitations of the above-ground characteristic LME model (Table 4.1) and any conclusions drawn from this statistical analysis are that the marginal R^2 values are small, which indicates there are missing factors that would better explain variance in tree seedling growth. These missing factors could include variables that were not measured in this study like the microclimatic conditions, the genetics and production conditions of the planted seedlings, or the soil nutrient levels. On the other hand, the marginal R^2 values of the below-ground characteristic LME model (Table 4.2), were much higher. This demonstrates that variables like below-ground biomass and ECM presence are valuable variables that explain variance in black spruce seedling growth. However, this increase in marginal R^2 values could be attributed to the smaller dataset used in Table 4.2. Overall, the conclusions presented with these models is that unfertilized black spruce seedlings grow at accelerated rates when they are planted in large volumes of dry soils with moderate cover of Sphagnum mosses and shrubs.

4.4 Conclusion

Overall, Rip and Lift mounds had the best seedling conditions and an above-average growth rate in 2020, 2021, and biennially. As a relatively new mounding practice in boreal peatlands, this was a welcome but unanticipated result. The conclusion that Rip and Lift mounds are highly beneficial to black spruce seedling growth deserves further research and examination on seismic lines. A study on the way Rip and Lift mounds alter the soil profile with their unique mounding methodology, as well as how this affects GHG emissions and rates of carbon sequestration would also be welcome to either support or oppose the continued use of Rip and Lift mounding. In terms of the original hypothesis on seedling conditions, it was corroborated that both Unmounded and Inverse Mounding treatments resulted in a higher proportion of seedling death. However, the high proportion of seedling death on Hummock Transfer mounds was unanticipated based on past research results. This may be attributed to the high percent cover of standing water surrounding the Hummock Transfer mounds, which is known to negatively impact seedling health (Morris et al., 2009).

Rates of seedling growth were less variable between mounding treatments than expected prior to the field research. The fact that these seedlings were measured only two years after mounding may not have provided enough time to show significant differences in overall growth. The results suggest that all treatments, including strategic planting on high locations of unmounded lines, lead to similar black spruce establishment but may not be indicative of long-term seedling survival. The hypotheses proposed prior to research were supported by this study as non-traditional mounds had slightly higher biennial growth patterns than Inverse mounding. An anticipated result was that Unmounded seedlings were not significantly shorter than black spruce seedlings planted on mounds. Further investigation on how Unmounded seismic lines could support planted seedlings over a decade time scale would be required to bolster the conclusions presented here.

The LME results were in line with the proposed hypothesis as soil moisture and mound height remained key variables influencing all measures of seedling growth rate. In LME models within Table 4.2, mound height was not a key effect, but ECM and below-ground biomass were introduced. Altogether these changes lead to the conclusion that while mound height is an easy characteristic to measure, the availability of dry rooting space paired with available soil nutrients is a better measure of seedling growth.

Chapter 5 – Effect of species and fertilization on planted tree seedling survival and growth

5.1 Introduction

There are two goals in this chapter: 1) to identify how tamarack growth rates differ across mounding methods and investigate the supporting and limiting factors of seedling growth for this species; 2) to identify how fertilization changes rates of seedling growth and the impacts of these changes across mounding methods and to identify the ideal growing conditions of fertilized black spruce and tamarack seedlings.

Seven datasets were used in this chapter with all data collected at the Brazeau site as tamarack seedlings and fertilization were not tested at Lac la Biche. In Section 5.2, the datasets include: 1) To identify seedling condition, a dataset of all unfertilized tamarack was used (n = 573); 2) To identify seedling growth rates across treatments, a dataset of all living, unfertilized tamarack was used (n = 572); 3) To investigate how characteristics of the surrounding microenvironment affect growth rates using a linear mixed effect model (LME), a dataset of all living, unfertilized tamarack planted on a seismic line was used (n = 548). Section 5.3 considered all fertilized tamarack that were alive and planted on the seismic line so only 4) one dataset with these characteristics was used (n=123). Finally, in Section 5.4, three datasets were used: 5) To determine seedling condition, a dataset of all fertilized black spruce was used (n=114); 6) To determine seedling growth and inform above-ground characteristic LME models, a dataset of all living fertilized black spruce was used (n=98). Finally, 7) a smaller dataset of fertilized black spruce with below-ground observations was used to perform a second set of LME models incorporating these effect variables (n=24)

This chapter aims to answer the following research questions:

1. What patterns can be observed in tamarack survival and growth rates across mounding treatments?
2. What characteristics best explain variance in tamarack growth rates? How do these characteristics interact with each other and directly affect seedlings? Are these characteristics more prevalent on any specific mounding treatment type?

3. To what extent does the application of slow-release NPK fertilizer affect the rates of growth and health conditions black spruce and tamarack seedlings?
4. What characteristics best explain variance in fertilized seedling growth rates? How do these characteristics interact with each other and directly affect seedlings? How do these characteristics change across species and mounding treatment?

Tamarack seedling condition and rate of growth were measured using a standardized methodology (Chapter 2). The hypotheses related to seedling condition and growth is that Unmounded areas would see the highest rates of seedling death and the lowest rates of seedling growth. As previous studies on seismic line mounding have concluded that mounding improves soil conditions for tamarack survival, Unmounded areas are unlikely to support tree growth to the same extent as non-traditional mounds (Pinzon, Dabros & Hoffman, 2022). The second hypothesis is that tamarack seedlings would be taller and have higher rates of growth than black spruce seedlings. Both black spruce and tamarack are highly adapted to peatland ecosystems, but previous studies have recorded that tamarack grow at a much faster pace across many classifications of growth including overall height, leader length, basal area, and total biomass (Hillman & Roberts, 2006).

The LME models were run with 28 unique characteristics, encompassing mound elevation (n = 3), soil moisture (n =8), vegetation communities (n = 10) and line characteristics (n = 7). The hypotheses associated with the LME models are that mound height and mound soil moisture characteristics would consistently be strong predictors for tamarack seedling growth. Studies reporting the benefits of high and dry mounds are common in the field of seismic line restoration (Davidson et al., 2020). Tamarack trees are known to prefer sun exposure whereas black spruce are shade-tolerant (Proulx et al., 2023). Based on physiological difference between species, it is likely that the level of canopy cover will be more important to tamarack seedling survival than black spruce.

Fertilization in this study was done with a slow-release bag of NPK fertilizer prills. N, P and K are all key nutrients that support tree growth, photosynthesis, and energy production. Nitrogen is known to be a limiting agent for seedling growth in peatlands (Mugasha & Pluth, 1994). For this reason, I hypothesize that the introduction of NPK fertilizer will increase black spruce and tamarack seedling condition and growth. Silfverberg’s (1995) study on peatland tree fertilization concluded that while N fertilization increased the survival rate of seedlings, growth rate was not affected. However, other studies have countered this conclusion with records of fertilization increasing black spruce growth (Ernfors et al., 2010). Another study on N fertilization concluded that excess N can extend the growing season of tamarack and fertilized tamarack kept their needles for 2 weeks longer than unfertilized treatments (Mugasha, Pluth & Macdonald, 1999). Studies into the effects of P and K fertilizer on both black spruce and tamarack trees have generally agreed that alone, P and K will not positively affect seedling growth and fertilization should include a high concentration of N (Mugasha & Pluth, 1994; Hillman & Takyi, 1998).

The final hypothesis on how fertilization will affect the ideal growing conditions of black spruce and tamarack seedlings is that with the introduction of more available soil nutrients, seedlings will have less competition with surrounding vegetation. With an abundance of resources, all vegetation growing on mounds should be less competitive; however, an increase in soil nutrients may also lead to an increase in surrounding plant biomass (Vitt et al., 2003). Bryophytes in particular are known to efficiently uptake soil nutrients in fertilizer application resulting in the danger that the majority of the fertilizer prills will be intercepted before the tree seedlings can benefit from the nutrients (Li & Vitt, 1996).

5.2 Results of unfertilized tamarack

5.2.1 Unfertilized tamarack seedling survivability

In Natural undisturbed areas, observed tamarack seedlings were in excellent health with 100% of samples classified as ‘Healthy’. The remaining seismic line sites also had excellent overall health of seedlings as all sites had over 90% of seedlings classified as ‘Healthy’. After Natural areas, Unmounded seismic lines had the highest percent of ‘Healthy’ seedlings (96%) and had even proportions of ‘Dead’, ‘Dieback with Regrowth and ‘Unhealthy’ seedlings (1.4%). However, this was the only treatment in which dead seedlings were observed. The overall survival rate for Unmounded sites was quite low, ranging between 72–82% (Appendix A). Rip and Lift treatments had the next highest proportion of ‘Healthy’ seedlings (94%). There were also low proportions of ‘Dieback’ (2.1%), ‘Dieback with Regrowth’ (1.7%) and ‘Unhealthy’ (2.1%) seedlings. Overall, the Rip and Lift condition proportions were average out of all seismic line sites. However, the calculated survival rate in this mounding treatment is very high, at 91%.

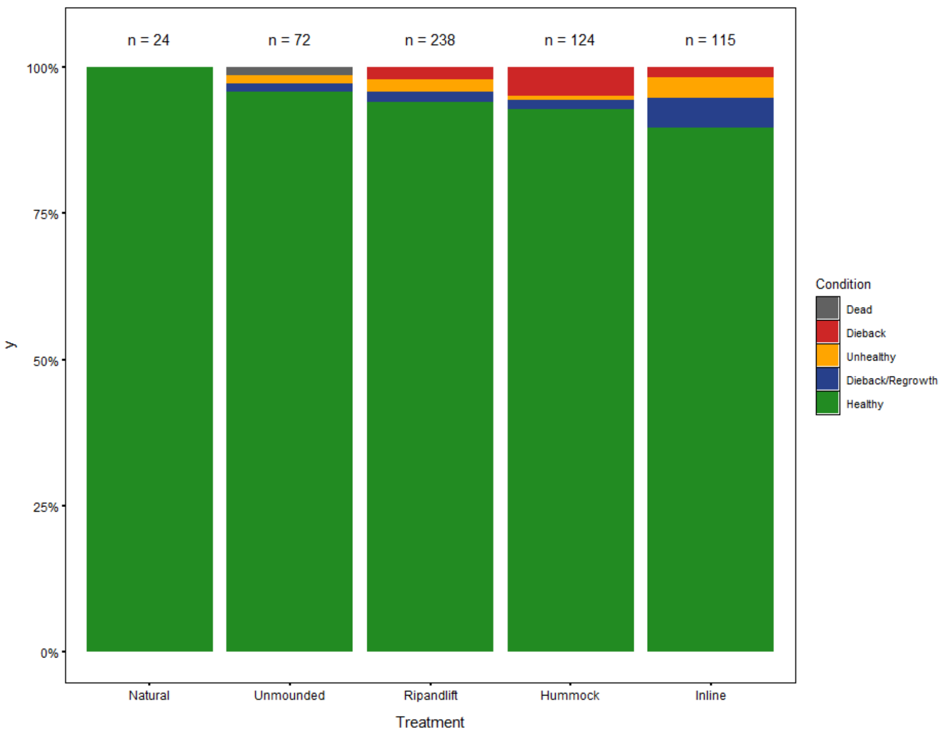

Figure 5.1: Percent proportion of tamarack seedling health condition by mounding method.

Hummock Transfer seedlings had a lower proportion of 'Healthy' seedlings (93%). In addition, this region had the highest proportion of dieback among tamarack at 5%. There were also minimal numbers of seedlings classified under 'Dieback with Regrowth' (2%) and 'Unhealthy' (1%). These mounds have a potential survival rate with a large range, 69–88% which makes an average survival rate of 78% the most likely. Finally, Inline mounds had the lowest proportion of 'Healthy' seedlings at 90%. Most of the remaining seedlings had dieback with regrowth at 5.2%, followed by smaller proportions of 'Unhealthy' (3.5%) and 'Dieback' (1.7%) seedlings. This mounding technique had the lowest survival rates of tamarack seedlings at 64–83%, showcasing the poorest outcomes for tamarack seedling survival and establishment than any other mounding treatment.

Comparing tamarack seedling condition to black spruce (section 4.2.1), there is a clear inter-species distinction. Tamarack seedlings are healthier than black spruce with almost double the proportion of 'Healthy' seedlings. In both datasets, Unmounded treatments had higher rates of seedling death than other treatments. However, tamarack seedlings saw above-average proportions of 'Healthy' seedlings while black spruce seedlings did not. Rip and Lift treatments across both species observed the best proportional distribution of seedling conditions with little seedling death and an above-average proportion of ‘Healthy’ seedlings. Both tamarack and black spruce Hummock Transfer seedlings had above-average proportions of ‘Healthy’ seedlings but tamaracks had a high proportion of dieback while the black spruce seedlings did not. Inline Mounding seedlings had similar condition patterns across both tree species with the low proportions of ‘Healthy’ seedlings and high proportions of ‘Dieback with regrowth’.

5.2.2 Unfertilized tamarack seedling growth

Overall, natural tamarack trees in undisturbed areas have consistently low rates of growth across both 2020 and 2021 growing seasons. The seismic line sites had much faster rates of growth in the 2020 growing season and slightly faster growth in 2021 compared to natural seedlings. For unfertilized tamarack seedlings, the 2020 growing season was the primary contributor to total seedling height at the time of sampling in late summer 2021.

Unmounded tamarack seedlings had the highest average growth in 2020. The distribution of leader lengths was left-skewed, but the interquartile range was the smallest of any seismic line site, indicating high consistency in tamarack growth across the Unmounded samples. In 2021, this pattern is reversed where Unmounded seedlings had the lowest rates of growth compared to other seismic lines sites (4.1 cm). Rip and Lift and Hummock Transfer seedlings both had average rates of growth across 2020 and 2021 growing seasons. Inline Mounding had a slightly lower rate of tamarack growth than other treatments in 2020 with an average of 15.9 cm. The pattern of distribution is also left-skewed, indicating that most seedlings with below-average growth rates in 2020 were not drastically lower than the average. In 2021, Inline Mounding seedlings had an above-average rate of growth, making them the fastest growing out of all seismic line treatments that year. When comparing seedling growth rates from 2020-2021 across treatments, there is very little difference in average growth with all biennial totals falling between 22.0 and 23.6 cm. In fact, there were no significant differences between treatments on seismic lines for 2020 annual growth ($F_{3,8}$=0.211; p=0.8859), 2021 annual growth ($F_{3,8}$=1.349; p=0.3256), or biennial growth ($F_{3,8}$=0.113; p=0.9499).

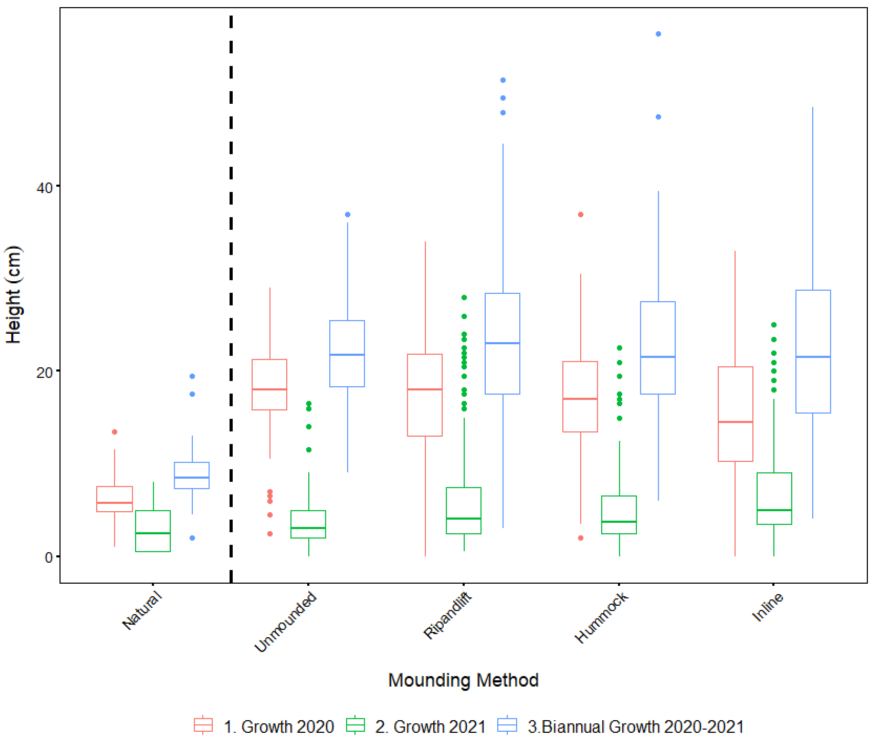

Figure 5.2: Unfertilized tamarack seedling growth measurements, second leader length in (cm) to determine 2020 annual growth, first leader length in (cm) to determine 2021 annual growth and calculated biennial (2020-2021) growth by mounding method.

Comparing the growth of both tree species planted, the most apparent difference is that tamarack seedling biennial growth (~22 cm) was approximately twice the amount of growth of black spruce seedlings (~13 cm). It is evident that tamarack and black spruce have different rates of growth in their initial establishment years. A main similarity between tree species is that neither species showed evidence of significant difference in biennial growth between non-traditional mounding techniques (section 4.2.2).

5.2.3 Characteristics supporting unfertilized tamarack seedling growth

A linear mixed effects model with backwards stepwise elimination isolates the effects that are the most likely to explain variance within the response variable of a dataset. The response variables used in this project are all measures of seedling growth, so all the effects listed in Table 5.1 are likely to explain change in unfertilized tamarack seedling growth.

Using an LME model with the response variable of 2020 annual growth, there was moderate evidence (p=0.0461) to suggest that four effects explained variance within the dataset.

These four effects include two continuous variables: the percent cover of other trees and the soil moisture recorded at the base of the seedling. The percent cover of other trees was positively correlated within the model, which suggests that the presence of other trees around the planted seedling improves seedling growth. The soil moisture at the tree was negatively correlated indicating that drier conditions would improve seedling growth. The other variables are categorical and include whether the tree was planted in a shaded spot and where the tree was planted relative to the hole dug on the seismic line disturbance. There is a slight decrease in 2020's annual growth for seedlings planted in shaded areas of the seismic line (μ=15.6 cm, σ=7.1) compared to those not shaded by the treeline (μ=16.8, σ=6.5). From the average leader length of tamarack in each category, it seems that tamarack have a slight increase in growth when planted near the hole or trench dug on the line in the case of Rip and Lift, Inline Mounding and Inverse Mounding (μ=17.2 cm, σ=7.3) with average growth planted centrally on the mound (μ=16.9 cm, σ=6.6) and slightly less growth far from the hole (μ=15.7 cm, σ=6.5). This would suggest that seedlings should not be planted too far from the hole or trench disturbance and there is no apparent benefit to moving the new mound soil far from the initial hole disturbance. Overall, with a marginal R^2 value of only 4.2%, this model explains little variance within the dataset and should not be considered a robust model for tamarack growth.

In 2021's growth model, the two effects most likely to explain variance in tamarack growth were the percent cover of moss ($p<0.0001$) and the height of the mound ($p<0.0001$). Looking at the correlation values, the presence of mosses is linked with a low annual growth rate and an increase in mound height is linked with an increased growth rate. Other factors likely to influence 2021's annual growth were the percent cover of other trees ($p=0.0054$), which increased growth rate, and the percent cover of Sphagnum moss ($p=0.0380$), which decreased the annual growth rate. The last two effects that contributed to variance in growth were the soil moisture at the tree ($p=0.0599$) and the percent cover of forb species ($p=0.0794$). As these effects were negatively and positively correlated, respectively, we would expect seedlings to grow best when the soil moisture is low and forb density is high. This model explained approximately 13% of the total variance in 2021 unfertilized tamarack growth.

Table 5.1 Results of linear mixed effects model of environmental parameters for unfertilized tamarack seedling growth from 2020 to 2021. Only significant parameters and interactions are shown.

Model Response Variable	Effect	Value	F	p-value	Marginal R^2	Conditional R^2
Annual Growth 2020	INTERCEPT	16.857	$F_{1,532}$= 264.95	<0.0001	0.042	N/A
	PC Tree	0.198	$F_{1,532}$= 4.00	0.0461		
	Soil Moisture at Tree	-0.028	$F_{1,532}$= 4.95	0.0265		
	Shaded	-----	$F_{1,532}$= 4.90	0.0273		
	Distance from Disturbance	-----	$F_{2,532}$= 3.37	0.0350		
Annual Growth 2021	INTERCEPT	7.352	$F_{1,531}$= 77.34	<0.0001	0.129	N/A
	PC Sphagnum	-0.036	$F_{1,531}$= 4.33	0.0380		
	PC Moss	-0.047	$F_{1,531}$= 34.74	<0.0001		
	PC Forbs	0.069	$F_{1,531}$= 3.09	0.0794		
	PC Tree	0.178	$F_{1,531}$= 7.81	0.0054		
	Height of Mound	0.087	$F_{1,531}$= 15.71	0.0001		
	Soil Moisture at Tree	-0.021	$F_{1,531}$= 3.56	0.0599		
Biennial Growth 2020-2021	INTERCEPT	25.836	$F_{1,531}$= 414.36	<0.0001	0.086	N/A
	PC Sphagnum	-0.037	$F_{1,531}$= 3.36	0.0674		
	PC Moss	-0.044	$F_{1,531}$= 10.56	0.0012		
	PC Shrubs	-0.091	$F_{1,531}$= 2.72	0.0999		
	PC Tree	0.376	$F_{1,531}$= 11.17	0.0009		
	Height of Mound	0.102	$F_{1,531}$= 9.37	0.0023		
	Soil Moisture at Tree	-0.054	$F_{1,531}$= 8.45	0.0038		

Comparing biennial growth models to singular year models, the greatest predictors of variance in growth were the replacement of forb cover with shrub cover, which was negatively correlated to growth, and the decrease in the marginal R^2 value to 8.6%. Overall, I conclude that the ideal conditions for unfertilized tamarack seedling growth are tall and dry mounds with lots of tree and forb cover but minimal shrub, Sphagnum, and other moss cover. Due to the low marginal R^2 values, there appear to be additional factors not measured in this study that would explain more variation in tamarack growth patterns.

Comparing black spruce and tamarack seedling conditions, it is clear that tamarack are growing faster and establishing as healthier seedlings. From the LME results, both species prefer a tall, dry mound that will promote high rates of seedling growth. The primary difference in black spruce and tamarack models are that black spruce seedlings have greater growth when planted in areas with high Sphagnum, lichen, shrub, and tree cover (section 4.2.3; section 4.2.4). Contrastingly, tamarack had decreased growth rates with high proportions of Sphagnum and shrubs but benefitted from high tree cover. Overall, we can conclude that having a tall, dry mound with some established vegetation will promote seedling growth regardless of the tree species planted.

5.3 Results of fertilized tamarack

5.3.1 Fertilized tamarack seedling survivability

All Natural tamarack were classified as ‘Healthy’ (Figure 5.1), but the tamarack planted on seismic lines did not achieve this level of healthy seedling condition when unfertilized. Within the population of fertilized tamarack, I did not observe any dead or unhealthy seedlings and all mounding treatment sites had over 88% ‘Healthy’ seedlings (Figure 5.3). Overall, seedling health was very good. Fertilized tamarack planted on Unmounded sections of seismic lines had the highest proportion of ‘Healthy’ seedlings (95%) with some seedlings classified under ‘Dieback with regrowth’ (5%). Unmounded treatments had the best seedling conditions at the time of sampling out of any fertilized seedling treatment. The calculated survival rate was 100% (Appendix A), showcasing that the fertilized tamarack seedlings were successfully establishing in the peatland.

Fertilized Rip and Lift seedlings had the lowest ‘Healthy’ proportion (88%) of any other fertilized tamarack treatment. This treatment also had the highest proportion of dieback among seedlings (7.1%) and a high proportion of dieback with regrowth’ (4.8%). The survival rate of these seedlings was only 84%, a low value compared to Unmounded and Hummock Transfer treatments. Fertilized Hummock Transfer seedlings had the second highest proportion of ‘Healthy’ seedlings (94%) and a moderate proportion of ‘Dieback’ seedlings (5.5%). These seedling conditions were similar to the Unmounded sections except that many damaged Hummock Transfer seedlings were not yet showing regrowth to their leaders and branches. The calculated survival rate was also 100% for fertilized seedlings in this treatment. Fertilized Inline Mounding seedlings had a lower proportion of ‘Healthy’ seedlings (92%) and the highest proportion of seedlings with dieback and regrowth (8%). The survival rate was also low at only 83%, making this treatment similar in condition and survival rate to Rip and Lift treatments.

Comparing the fertilized tamarack seedling condition results to the unfertilized discussed in section 5.2.1, the fertilized tamarack had 0% seedling death compared to unfertilized (0.17%). Both fertilized and unfertilized tamarack had similar proportions of 'Healthy' seedlings around 93%.

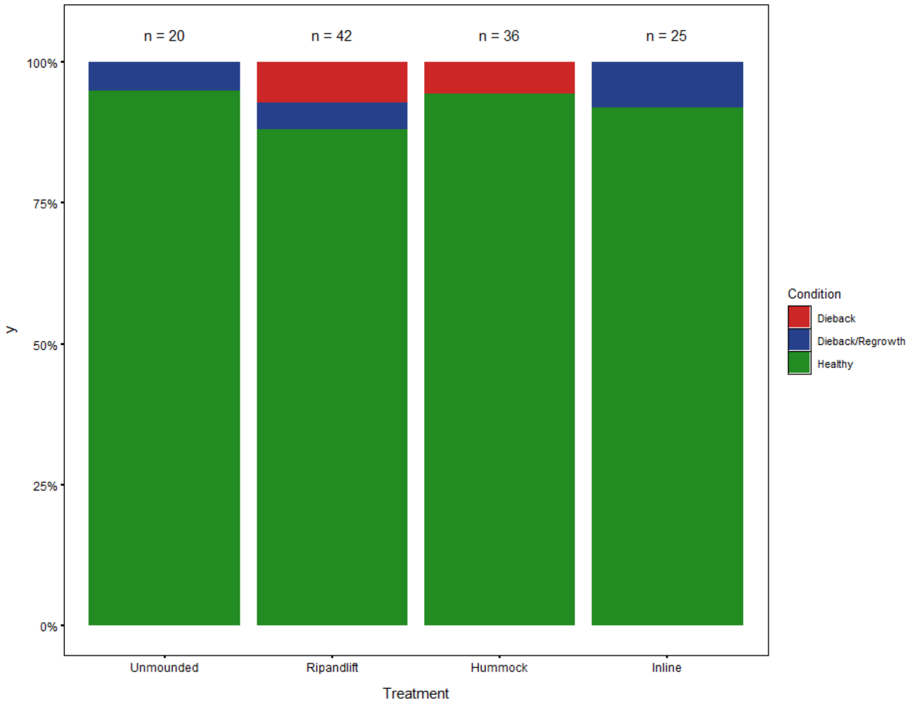

Figure 5.3: Percent proportion of fertilized tamarack seedling health condition by mounding method.

5.3.2 Fertilized tamarack seedling growth

Tamarack seedlings planted with fertilizer show different patterns in growth to unfertilized tamarack (Figure 5.4). In Unmounded regions, the fertilized seedlings had the highest rate of growth in 2020 but the lowest rate of growth in 2021. Overall, Unmounded seedlings had an average biennial growth rate (27 cm) compared to other treatments. This pattern in growth is identical to unfertilized tamarack and shows consistency in Unmounded tamarack growth regardless of fertilization. Rip and Lift seedlings had average growth rates across all three measures of growth. However, their biennial growth distribution is the most left-skewed, indicating that the lowest half of seedlings are clustered close to the mean. Fertilized seedlings on Hummock Transfer mounds had consistent high rates of growth as the second highest average treatment in both 2020 and 2021. Overall, this consistently high rate of growth makes fertilized

Hummock Transfer tamarack seedlings the fastest growing biennially out of all mounding treatments. Seedlings planted on Inline mounds had similar rates of growth across 2020 and 2021 but compared to other mounding treatments, their rates of growth were low to average, making their overall biennial growth the lowest of all Brazeau treatment plots.

The annual growth of fertilized seedlings in 2020, the first year post-planting and fertilization, was significantly different among mounding treatments (ANOVA, $F_{3,7}$=11.702; p=0.0016) with strong evidence that Unmounded (p=0.0034) and Hummock Transfer (p=0.0015) seedlings had greater growth than Inline Mounding seedlings. There was also weak evidence to support Unmounded (p=0.0890) and Hummock Transfer (p=0.0635) seedlings having greater growth than Rip and Lift seedlings. There were no significant differences between mounding treatments for the 2021 annual growth ($F_{3,7}$=1.773; p=0.3406). However, biennially, there was evidence that Hummock Transfer seedlings ($F_{3,7}$=3.557; p=0.0165) had higher growth rates than either Inline Mounding (p=0.0389) or Rip and Lift seedlings (p=0.0307).

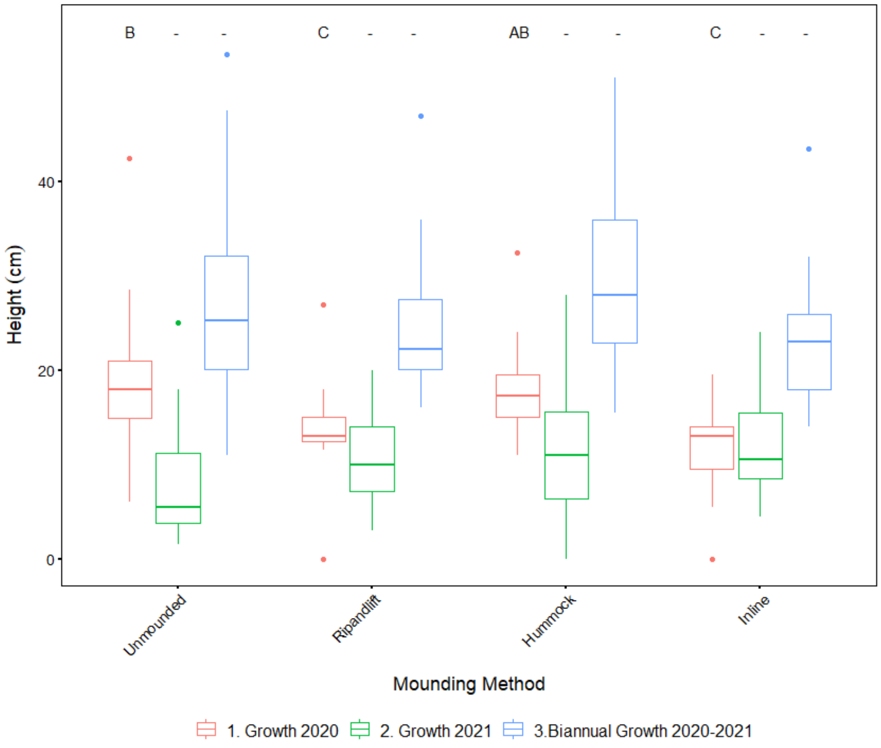

Figure 5.4: Fertilized tamarack seedling growth measurements, second leader length in (cm) to determine 2020 annual growth, first leader length in (cm) to determine 2021 annual growth and calculated biennial (2020-2021) growth by mounding method. Significant differences displayed above in letter notation and should be compared only within one growth period.

When comparing patterns in growth data between fertilized and unfertilized tamarack, fertilized tamarack (26 cm) has slightly higher growth than unfertilized (23 cm) (Figure 5.5). This difference is statistically significant with strong evidence that fertilized tamarack have higher rates of growth than unfertilized tamarack biennially (ANOVA, $F_{1,1385}$=30.620; p= 0.0026), and in 2021 ($F_{1, 1385}$=5.724; p= 0.0001) but not in 2020 ($F_{1, 1385}$=5.036; p= 0.6594).

On Unmounded sites, both fertilized and unfertilized tamarack had a similar pattern of high growth in 2020 and lower growth in 2021 (Figure 5.5). In 2020 the actual amount of growth was similar regardless of fertilization at approximately 18 cm, but in 2021, fertilized tamarack growth was twice as much at approximately 8 cm ($F_{1, 1385}$=16.343; p=0.0001). Overall, fertilization significantly improved the biennial growth rate of tamarack seedlings ($F_{1, 1385}$=6.985; p=0.0097). Rip and Lift seedlings remain consistent in their average values compared to other mounding treatments, with no observed differences in growth with the application of fertilizer. Fertilized Hummock Transfer seedlings had increased rates of growth with fertilizer in every growth category with 2020 ($F_{1, 1385}$=3.913; p=0.0497), 2021 ($F_{1, 1385}$=28.461; p<0.0001) and biennially ($F_{1, 1385}$=18.057; p<0.0001). The increase in growth rates with the application of fertilizer was the most evident within this treatment. Inline mounds had similar patterns of growth as Hummock Transfer mounds as the application of fertilizer increased growth rates in 2021 ($F_{1, 1385}$=10.230; p=0.0017) and biennially ($F_{1, 1385}$=5.439; p=0.0212), but not in 2020 ($F_{1, 1385}$=0.064; p=0.8011). Overall, the fertilization of tamarack seedlings resulted in 3 cm more growth; this represents a 15% increase in seedling growth.

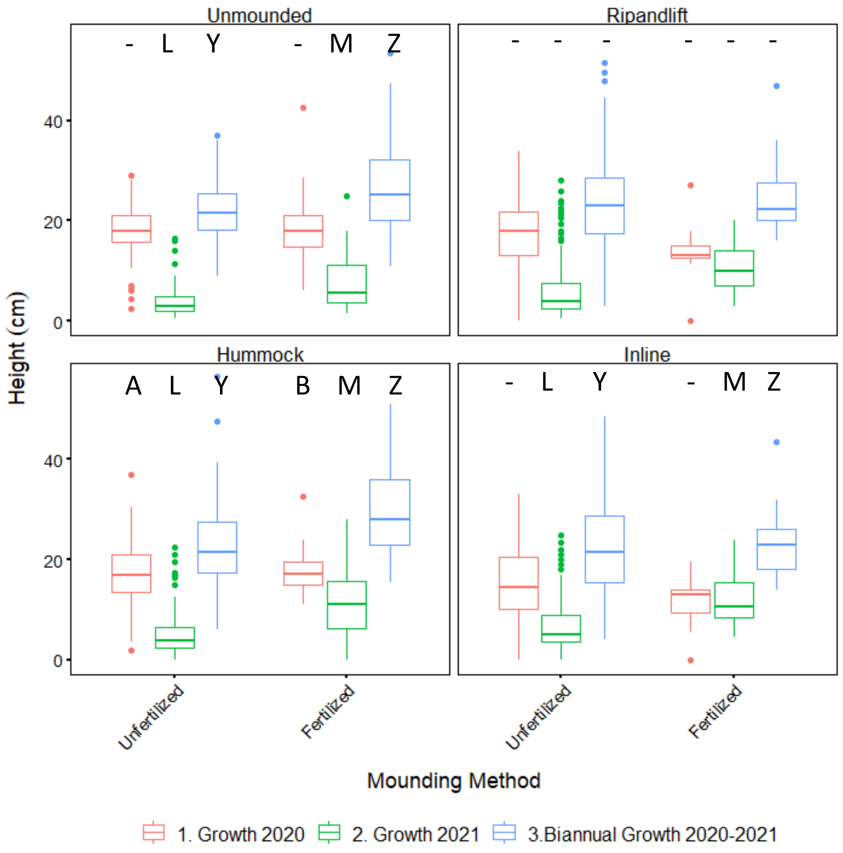

Figure 5.5: Fertilized versus unfertilized tamarack seedling growth measurements by mounding method. Significant differences within each mounding treatment type displayed above in letter notation.

5.3.3 Characteristics supporting fertilized tamarack seedling growth

When applying a linear mixed effects model to a response variable of 2020’s annual growth for fertilized tamarack, there was only one effect that presented enough evidence to explain variance within the dataset. This effect was the relation to the line (p=0.0280) which is a categorical variable classifying where the mound is located across the seismic line. Fertilized tamarack planted on mounds located near the center of the seismic line, had the lowest average growth rate of 13.8 cm (σ=4.1 cm). Seedlings planted on mounds near the sides of the seismic line, had much greater rates of growth in 2020 with seedlings on the East edge of the line having a slightly greater average growth (μ=16.3 cm; σ=6.3 cm) than the West edge of the line (μ=15.1 cm; σ=4.7 cm). Overall, this effect only explains a small portion of the variance (6.2%) within the dataset (Table 5.2).

Modeling with a response variable of 2021’s annual growth, the effects that were highly likely to explain variance within the dataset were the line width (p=0.0164) and the distance from disturbance (p=0.0379). The negative correlation of growth and line width within the model indicates that fertilized tamarack seedlings will grow best on narrow lines. Concerning the distance from the disturbance, seedlings farthest from the disturbance have slightly better growth (μ=15.6 cm; σ=5.8 cm) than those centrally located (μ=15.4 cm; σ=5.4 cm) or near the disturbance (μ=14.6 cm; σ=4.9 cm), opposite to the response observed for unfertilized seedlings (Table 5.3). However, the difference between these averages was very small, and the large standard deviation for seedlings planted far from the disturbance may indicate that the mean may be influenced by more extreme values. The other effects that play a role in explaining 2021 growth of fertilized tamarack were height of the mound (p=0.0678), which is positively correlated in the model, and the soil moisture at the mound peak (p=0.0753) and the soil moisture at the tree (p=0.0627) with weak evidence that they are both negatively correlated to seedling growth. The marginal R^2 value for this model is 15.8%.

Table 5.2 Results of linear mixed effects model of environmental parameters for fertilized tamarack seedling growth from 2020 to 2021. Only significant parameters and interactions are shown.

Model Response Variable	Effect	Value	F	p-value	Marginal R^2	Conditional R^2
Annual Growth 2020	INTERCEPT	13.597	$F_{1,117}$= 85.68	<0.0001	0.062	N/A
	Relation to the Line	-----	$F_{2,117}$= 3.79	0.0280		
Annual Growth 2021	INTERCEPT	2.024	$F_{1,113}$= 520.57	<0.0001	0.158	0.158
	Line Width	-0.491	$F_{1,113}$= 5.94	0.0164		
	Height of Mound	0.101	$F_{1,113}$= 3.40	0.0678		
	Soil Moisture at Peak	-0.037	$F_{1,113}$= 3.22	0.0753		
	Soil Moisture at Tree	-0.062	$F_{1,113}$= 3.53	0.0627		
	Distance From Disturbance	-----	$F_{2,113}$= 3.37	0.0379		
Biennial Growth 2020-2021	INTERCEPT	27.285	$F_{1,118}$= 355.32	<0.0001	0.027	N/A
	Soil Moisture at Peak	-0.067	$F_{1,118}$= 3.31	0.0713		

Finally, when modeling total growth from 2020 and 2021, we see that the model explains much less variation in growth than either 2020 or 2021 alone, with a marginal R^2 value of only 2.7%. The only notable effect in this model is the soil moisture at the peak of the mound (p=0.0713) which only provides weak evidence that drier mound peaks will improve seedling growth. Overall, fertilized tamarack seedling growth can be promoted by planting seedlings on narrow seismic lines with tall, dry mounds. Prioritizing planting on mounds located close to the edges of the seismic lines, might also be prudent to maximize success.

To compare the ideal conditions of unfertilized and fertilized tamarack seedlings, we see that when a tamarack seedling is fertilized the surrounding vegetation communities are less important. A common pattern among tamarack seedlings is an importance on mound characteristics, where tall and dry mounds are key factors that reliably promote seedling growth. Factors relating to mound placement, like line width, where the mound is in relation to the line, and where the seedling is planted on the mound are likely important factors influencing both unfertilized and fertilized seedling growth.

5.4 Results of fertilized black spruce

5.4.1 Fertilized black spruce survivability

As discussed in section 4.2.1, Natural black spruce trees had excellent seedling health with 89% of trees within the ‘Healthy’ category. Comparatively, the fertilized black spruce had a total proportion of ‘Healthy’ seedlings from 73%-56%, much lower than the Natural trees. Looking at fertilized Unmounded seedlings, they had the lowest proportion of ‘Healthy’ seedlings (56%). A full third of all seedlings were classified as ‘Unhealthy’, a much higher proportion than any other fertilized site. The proportion of ‘Dieback’ and ‘Dieback with Regrowth’ were also high (5.6%). A notable characteristic is that the Unmounded treatment was the only one to have zero observed dead seedlings. This is a significant observation since 90% of the recorded planted seedlings were found on site. Overall, due to the lack of dead seedlings, Unmounded regions still show the best conditions for fertilized seedling establishment. Rip and Lift treatments had an average proportion of ‘Healthy’ seedlings among all treatments assessed (67%) and the second lowest proportion of ‘Dead’ seedlings (11%). The proportion of ‘Unhealthy’ seedlings was similar to the dead at 14% while the damaged classifications of ‘Dieback’ (5.6%) and ‘Dieback with Regrowth’ (2.8%) were most similar to each other. Overall, Rip and Lift seedlings had average condition proportions compared to all other mounding treatments, with a moderate proportion of each condition classification. However, the Rip and Lift survival rate was the lowest overall at only 70%. Hummock Transfer treatments had the highest proportion of 'Healthy' seedlings (73%). The proportion of dead seedlings was similar to Rip and Lift at 12%; however, the proportion of unhealthy or damaged seedlings was lower. The rate of seedling survival was over 100%, indicating a planting record error (or that some natural regeneration trees were counted) but still suggesting that a very high rate of seedlings survived two years post-planting. Inline mounds had the highest proportion of seedling death of any other recorded treatment (30%). This rate is more than double that for any other mounding treatment regardless of species or fertilization. However, there were low proportions of other damaged seedling conditions like 'Unhealthy' (3.7%) and 'Dieback with Regrowth' (3.7%). The proportion of 'Healthy' seedlings was just below-average at 63%. Interestingly, although the proportion of dead seedlings was very high, the overall survival rate was good at 90%.

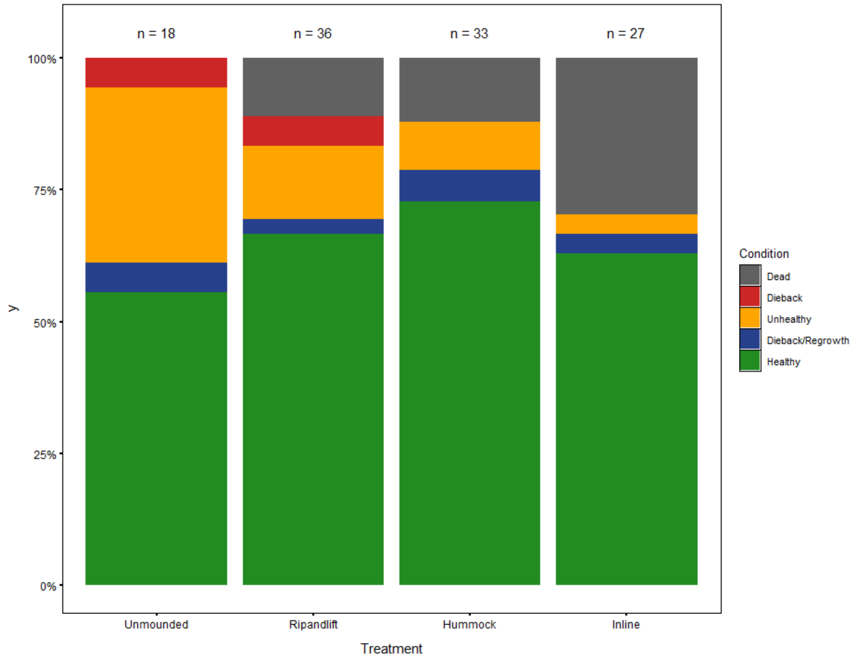

Figure 5.6: Percent proportion of fertilized black spruce seedling health condition by mounding method.

To compare the fertilized black spruce against unfertilized black spruce seedlings (see section 4.2.1) fertilized seedlings had a higher proportion of 'Healthy' (Δ7%) and 'Dead' (Δ10%) seedlings. This suggests that fertilizer application causes a dual reaction on black spruce seedlings where it can both improve or worsen seedling health. The sample size of fertilized seedlings is smaller and isolated to only one section of the study site which may play a role in this comparison. Also, the rate of unfertilized black spruce death may be disproportionate, because more fertilized black spruce (90%) were found on the seismic line than unfertilized black spruce (68%). It is difficult to conclude if fertilization helped or hindered black spruce establishment since there were fewer missing fertilized seedlings and more observed dead seedlings.

Overall, it is clear that fertilization is an effective method for decreasing tamarack seedling death, but my data does not show that it has an advantage for black spruce seedling establishment. As a known limitation to this conclusion, fertilization plots were only present on the Brazeau South Line, but these conditions were compared with unfertilized seedlings across the entirety of the Brazeau site.

5.4.2 Fertilized black spruce seedling growth

Naturally established black spruce trees grew an average of 7 cm in 2020 and 4 cm in 2021 (Figure 4.2, section 4.2.2). Fertilized black spruce seedlings also showcase a decrease in average growth from 2020 to 2021. Seedlings in Unmounded areas had the second highest average growth in 2020 and the distribution had a strong left-skew, indicating that the lowest half of seedlings still had a growth rate close to the median of 9 cm. In 2021, Unmounded seedlings had the highest average growth, and biennially fertilized Unmounded seedlings had the overall highest average growth. Fertilized Rip and Lift seedlings had average rates of growth in 2020 and 2021 compared to other mounding methods. However, their biennial growth from 2020-2021 was the second highest at 16 cm. Fertilized Hummock Transfer seedlings had the highest average growth rate in 2020, however, their 2021 growth rate was very low compared to other mounding methods. Inline seedlings had consistently lower than average growth rates in 2020 and 2021. Overall, the biennial growth of fertilized Inline seedlings was slightly below average at 13.2 cm compared to other fertilized treatments.

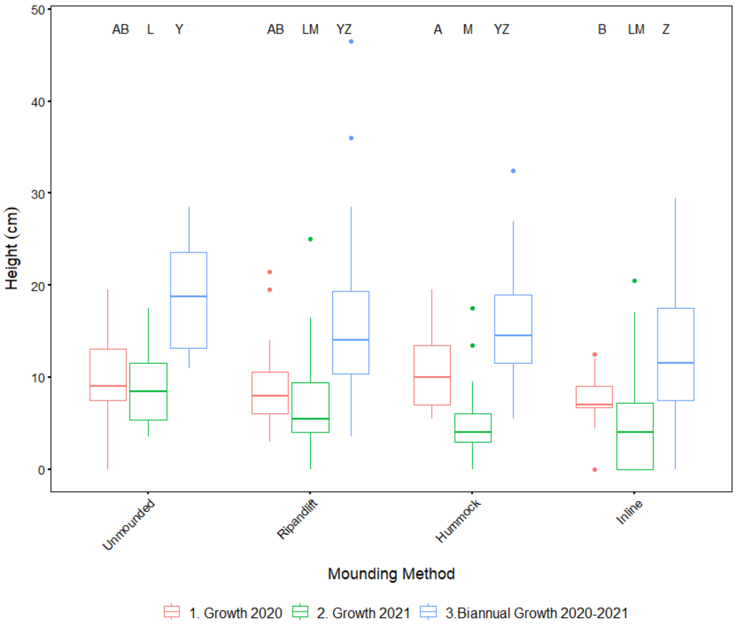

Figure 5.7: Fertilized black spruce seedling growth measurements, second leader length in (cm) to determine 2020 annual growth, first leader length in (cm) to determine 2021 annual growth and calculated biennial (2020-2021) growth by mounding method. Significant differences displayed above in letter notation.

Examining the statistical difference in growth of fertilized seedlings among mounding methods, an ANOVA for 2020's growth ($F_{3,7}$=3.951; p=0. 0104) provided moderate evidence that, when fertilized, Hummock Transfer black spruce seedlings had higher growth rates than Inline Mounding seedlings (p=0.0122). In 2021, an ANOVA ($F_{3,7}$=3.301; p=0.0234) indicated with moderate evidence that Unmounded seedlings had higher average growth than Hummock Transfer seedlings (p=0.0338). Finally, significant differences in biennial growth were highlighted in the ANOVA ($F_{3,7}$=2.136; p=0.1003) where weak evidence was presented to support Unmounded seedlings having greater growth than Inline Mounding seedlings (p=0.0644). No other evidence of significant difference was found.

To compare planted black spruce seedling growth between fertilized and unfertilized controls, there are different patterns of growth among mounding treatments when seedlings are fertilized (Figure 5.8). Within Unmounded treatments, fertilization increased growth in 2021 ($F_{1,72}$=61.816; p<0.0001) and biennially ($F_{1,72}$=29.012; p<0.0001) to a large extent with fertilized seedlings having on average 7 cm or a 60% increase in biennial growth than unfertilized seedlings. The 2021 increase in Hummock Transfer ($F_{1,243}$=3.329; p=0.0012) treatments provided some evidence that fertilization could provide minor increases in overall rates of growth. Finally, while Inline Mounding treatments saw an increase in growth with fertilizer in 2021's growing year ($F_{1,135}$=13.036; p=0.0004), this was the only mounding treatment to see a minor decline in fertilized seedlings biennial growth rates ($F_{1,135}$=5.297; p=0.0229). Overall, the fertilization of black spruce seedlings is beneficial in Unmounded areas but produces little effect within other mounding treatments. Overall, the fertilization of black spruce seedlings resulted in 2.5 cm more growth; this can also be calculated as a 20% increase in seedling growth.

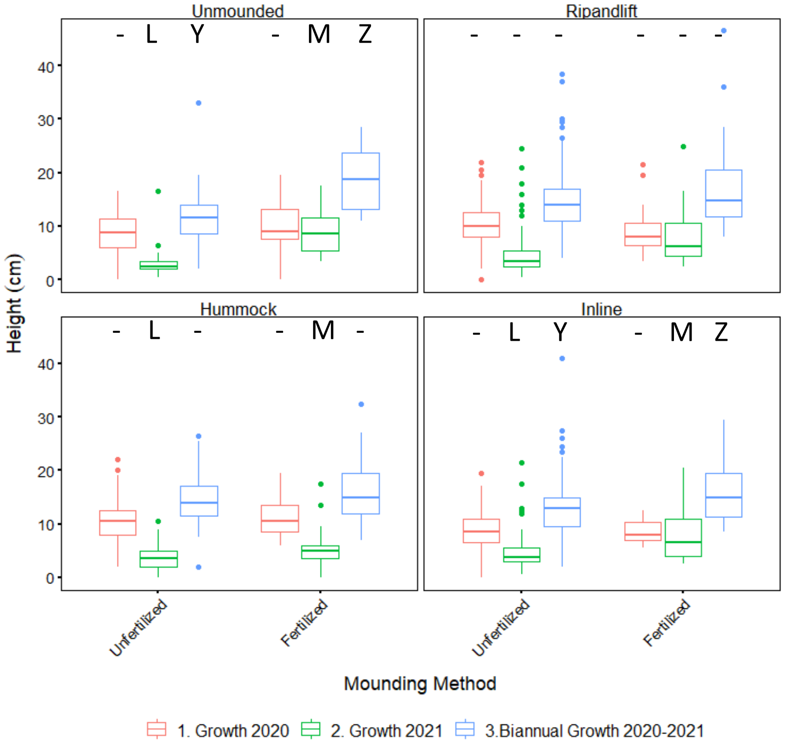

Figure 5.8: Fertilized versus unfertilized black spruce seedling growth measurements by mounding method. Significant differences within each mounding treatment type displayed above in letter notation and should be compared only within a growth period.

5.4.3 Characteristics supporting black spruce seedling growth

Looking at the annual growth model for 2020, the most likely factors to influence growth of fertilized black spruce seedlings were the total percent cover of vegetation (p=0.0394) and the soil moisture at the peak of the mound (p=0.0383). Since the values of these factors are negative and positive, respectively (Table 5.3), this indicates that fertilized black spruce grow best on mounds with lower vegetative cover and higher soil moisture at the peak. Other notable effects include the percent cover of Sphagnum and bare soil, both of which were negatively correlated in the model. The distance from disturbance effect is a categorical variable classifying seedlings based on their placement on the mound. The black spruce planted closest to the hole or trench disturbance on the seismic line had the best growth in 2020 with an average of 10.9 cm (σ = 4.3). Seedlings planted on the centre of the mound had an average of 9.4 cm of growth (σ = 4.0) and those planted farthest had the least average growth at 8.3 cm (σ = 3.8). Overall, these five effects provided a limited explanation of variance within the dataset with a marginal R^2 value of 16.6%.

Table 5.3 Results of linear mixed effects model of environmental parameters for fertilized black spruce seedling growth from 2020 to 2021. Only significant parameters and interactions are shown.

Model Response Variable	Effect	Value	F	p-value	Marginal R^2	Conditional R^2
Annual Growth 2020	INTERCEPT	265.295	$F_{1,104}$= 113.86	<0.0001	0.166	N/A
	PC Sphagnum	-0.020	$F_{1,104}$= 3.56	0.0620		
	PC Soil	-1.624	$F_{1,104}$= 3.28	0.0730		
	Total Vegetation Cover	-2.553	$F_{1,104}$= 4.35	0.0394		
	Soil Moisture at Peak	0.041	$F_{1,104}$= 4.40	0.0383		
	Distance from Disturbance	-----	$F_{2,104}$= 2.49	0.0879		
Annual Growth 2021	INTERCEPT	9.176	$F_{1,107}$= 175.27	<0.0001	0.120	0.127
	Line Width	-1.148	$F_{1,107}$= 2.96	0.0880		
	PC Forbs	0.127	$F_{1,107}$= 3.32	0.0713		
	Height of Mound	0.169	$F_{1,107}$= 8.78	0.0038		
Biennial Growth 2020-2021	INTERCEPT	15.554	$F_{1,107}$= 558.35	<0.0001	0.126	0.127
	PC Sphagnum	-0.035	$F_{1,107}$= 3.50	0.0642		
	Height of Planting	0.176	$F_{1,107}$= 8.38	0.0046		
	Difference in tree and peak soil moisture	-0.067	$F_{1,107}$= 4.45	0.0372		

In the 2021 growth model, an effect highly likely to explain variance in growth of fertilized black spruce was the height of the mound (p=0.0038) with an increase in mound height resulting in an overall increase in annual growth. Other effects noted in this model were line width and the percent cover of forb species. With negative and positive regression values respectively, we would expect fertilized black spruce seedlings to grow best on narrow sections of seismic line with greater forb cover. Overall, these effects explain 12% of the total variance in 2021 growth among unfertilized black spruce.

Table 5.4 Results of linear mixed effects model of environmental and laboratory parameters for fertilized black spruce seedling growth from 2020 to 2021. Only significant parameters and interactions are shown.

Model Response Variable	Effect	Value	F	p-value	Marginal R^2	Conditional R^2
Annual Growth 2020	INTERCEPT	289.46	$F_{1,18}$ = 259.27	<0.0001	0.380	0.403
	PC Soil	-1.532	$F_{1,18}$ = 8.98	0.0077		
	Total Vegetation Cover	-2.801	$F_{1,18}$ = 5.45	0.0314		
Annual Growth 2021	INTERCEPT	5.184	$F_{1,17}$ = 53.82	<0.0001	0.622	N/A
	PC Tree	2.475	$F_{1,17}$ = 10.65	0.0046		
	Height of Mound	0.270	$F_{1,17}$ = 12.65	0.0024		
	%Ectomycorrhizal Presence	-0.210	$F_{1,17}$ = 9.86	0.0060		
Biennial Growth 2020-2021	INTERCEPT	209.06	$F_{1,13}$ = 540.39	<0.0001	0.713	0.713
	PC Sphagnum	-0.105	$F_{1,13}$ = 7.09	0.0195		
	PC Forbs	0.357	$F_{1,13}$ = 6.60	0.0233		
	PC Graminoids	-0.183	$F_{1,13}$ = 13.41	0.0029		
	PC Tree	2.697	$F_{1,13}$ = 7.23	0.0185		
	Total Vegetative Cover	-1.872	$F_{1,13}$ = 9.30	0.0093		
	Height of Mound	0.362	$F_{1,13}$ = 8.74	0.0111		
	%Ectomycorrhizal Presence	-0.210	$F_{1,13}$ = 4.66	0.0501		

Modeling both 2020 and 2021 growth variables together as biennial growth, the linear mixed effects model identified three notable effects (Table 5.3). The height of planting is highly likely to explain variance (p=0.0046), the difference in soil moisture from the seedling to the mound peak is also a moderately likely effect (p=0.0372), while a less likely effect of Sphagnum cover was also identified (p=0.0642). Assessing these effects, I conclude that fertilized black spruce seedlings are more likely to have greater biennial growth when they are planted at a taller height on the mound, are wetter than the mound peak, and have less Sphagnum cover.

A linear mixed effects model using a dataset of fertilized black spruce seedlings and including the physical and ectomycorrhizal characteristics, produced the results seen in Table 5-4. Using 2020's annual growth as the response variable, two effects were identified as likely explanations for variance within the dataset: the percent cover of bare soil (p=0.0077) and the total vegetative cover (p=0.0314). Both of these effects had a negative value, meaning that an increase in these characteristics is usually paired with a decreased rate of growth in the sample seedling. This leads to the conclusion that to promote seedling growth, mounds should not have excess bare soil, but they should also not be fully vegetated. Together, these two variables are important to promote growth since they explain 38% of variance within the dataset.

Focusing on the variance within 2021's growth variable, the percent cover of other trees (p=0.0046), the height of the mound (p=0.0024) and the presence of ectomycorrhiza (p=0.0060) are all highly likely to explain difference in growth between seedlings. From their correlation values, the percent cover of trees and the height of the mound were positively correlated to growth. On the other hand, the ectomycorrhizal presence was negatively correlated with growth and thus may be present in higher densities on seedlings struggling to adapt to their planting location. These variables account for over 62% of total variance within the dataset, therefore it is a good model to use to measure 2021's annual growth rates for fertilized black spruce seedlings.

Looking at both year's growth together under the Biennial Growth 2020-2021 LME model, the marginal R^2 value is over 70%, making this model a very good fit to explain variance within the dataset. From this there were two effects highly likely to contribute to the explanation of variance, the percent cover of graminoids species (p=0.0029) and the total vegetative cover (p=0.0093). These effects were negatively correlated with growth indicating better growth with less vegetation cover for fertilized black spruce. Other factors that may limit seedling growth in this model are the percent cover of Sphagnum (p=0.0195) and the presence of ectomycorrhiza (p=0.0501). Effects that were positively linked to seedling growth were the percent cover of forb species (p=0.0233), the percent cover of other trees (p=0.0185) and the height of the mound (p=0.0111). In conclusion, these seedlings grow best when they are planted on tall mounds with other tree and forb species with minimal Sphagnum, graminoid and other vegetative cover. The presence of ectomycorrhiza is also linked to lower tree growth.

The patterns observed in the LME models for unfertilized (Chapter 4) and fertilized black spruce seedling are quite different. Firstly, the role of lichen and moss cover is not as important with fertilized seedlings; the benefit of lichen and the hindrance of moss species is not as apparent in the fertilized seedling dataset. In addition, the percent cover of Sphagnum was positively correlated to growth in unfertilized seedlings, but negatively correlated to growth in fertilized seedlings. Comparing the robustness of the above LME models to those in section 4.2.3 regarding black spruce seedlings planted without fertilizer, there was generally a large increase in marginal R^2 values for fertilized seedling models. As the marginal R^2 value is a measure of how well the model explains variances with a dataset, fertilized black spruce data is better explained by LME models than unfertilized seedling data.

5.5 Discussion

5.5.1 Trends in unfertilized tamarack seedling growth and condition

Biennially, there is a clear trend in unfertilized tamarack growth where seedlings had greater growth in 2020 than in 2021. Mounding treatment, or lack thereof, did not make a significant difference in tamarack growth rates. Compared to black spruce, tamarack seedlings grew approximately twice as much biennially. This extreme difference in growth rates is not unprecedented in black spruce and tamarack comparison studies. It is well known that tamarack seedlings grow faster and taller than black spruce in their initial stages of growth (Hillman & Roberts, 2006). Black spruce and tamarack had similar annual growth patterns, where neither species showed significant differences in growth between Unmounded and non-traditional mounding practices. This supports the conclusion that regardless of tree species, non-traditional mounding and targeted planting approaches result in similar seedling rates of growth. Inverse mounding exhibited a negative influence on black spruce seedlings (Chapter 4) however, further research on tamarack and Inverse mounding is required to confirm if this trend also applies across species.

The seedling health conditions of unfertilized tamarack varied across mounding treatments. Overall, most Unmounded seedlings were in excellent health compared to seedlings planted on non-traditional mounds. These excellent health conditions are very different to the health conditions observed in unfertilized black spruce. Observations classified approximately 50% of black spruce seedlings as dead, damaged or unhealthy. As black spruce and tamarack seedlings were planted in pairs on the same mounds, this difference in seedling condition cannot be attributed to the surrounding environmental conditions. There were many observations in the field where two species planted side-by-side had drastically different health conditions. It is unlikely that interspecies competition plays a large role in seedling health conditions. Black spruce tends to be the more competitive species as shown in Wagner & Robinson's (2006) study, black spruce had higher survival rates than four other conifer species 5 years post-planting. Therefore, the reasons behind this difference in seedling condition is likely due to the physiological differences between black spruce and tamarack species.

Both black spruce and tamarack are adapted to a peatland ecosystem and were naturally present at the study site. However, black spruce are known to be highly shade-tolerant while tamarack are better adapted to sunnier conditions (Proulx et al., 2023). As seismic lines have a completely open canopy, this may provide greater benefits to tamarack growth than black spruce growth. Another physiological difference between species is their adventitious root systems. Both black spruce and tamarack grow adventitious roots (shallow roots formed at the base of the tree) (Veverica, Kane & Kasischke, 2012). These roots help the trees adapt to the harsh conditions of peatlands as they provide additional nutrient uptake, maintain a steady water balance and protect seedlings in flooded soil conditions (Pernot, Thiffault & DesRochers, 2019). A difference in the mass of adventitious roots between black spruce and tamarack species might explain why seedling health condition was different between species. To investigate this further, a study on the role of tamarack and black spruce adventitious roots would help support or eliminate this as a limiting factor of seedling growth. The final physiological difference that would negatively influence black spruce growth rates are the fact that black spruce often form multiple leaders (Wagner & Robinson, 2006). Multiple leadering creates a denser volume of branches at the expense of a taller stem. As tamarack are less likely to develop multiple leaders, there would be less of an impact on the overall average height of seedling growth. To confirm the impact of multiple leadering in black spruce seedlings on the total rate of growth, incidences of multiple leadering should be reported in future field observations.

5.5.2 The ideal growth conditions of unfertilized tamarack seedlings

Unfertilized tamarack seedlings grew at a faster rate when planted on tall, dry mounds with moderate tree and forb cover but minimal shrub, Sphagnum, and moss cover (Table 5.1). This supports the conclusion that tamarack seedlings are in competition with woody shrubs and bryophytes, but might benefit from a higher planting density of tree seedlings on mounds. The addition of trees on mounds would increase the competition for resources with shrub species and help shade out bryophytes growing around the planted seedlings. The negative impact of high soil moisture on tamarack is in line with previous studies on peatland trees that have continually supported the conclusion that water-saturated soils on seismic lines provide an unsuitable environment for seedling establishment (Langdon, Dovciak & Leopold, 2020). Similarly, my results (Table 5.1) and previous studies conclude that tall mounds encourage drier conditions that positively impact tamarack seedling health, growth, and overall establishment (Filicetti, Cody & Nielsen, 2019).

Compared to the ideal conditions investigated for planted black spruce seedlings, tamarack have a different relationship with shrubs and Sphagnum cover. In addition, there is greater correlation with the planting location relative to the hole or trench left on the seismic line. Black spruce seedlings have a positive relationship with shrubs and Sphagnum cover (Table 4.1) while tamarack have a negative relationship. Shrubs and tamarack seedlings are strongly competitive for direct sunlight (Hébert et al., 2010). However, black spruce seedlings are a more shade tolerant species and may not be impacted by shrubs in the same way as tamarack (Proulx et al., 2023). Tamarack seedlings are less adaptable to acidic conditions than black spruce, and may be more impacted by the increases in soil acidity characterised by long term Sphagnum presence (Granath, Strengbom & Rydin, 2010). New variables introduced in unfertilized tamarack seedling models were categorical variables concerning seedling placement on the seismic line. Tamarack grew at a faster rate when planted in areas that were less shaded by the seismic line edge canopy. This is consistent with the knowledge that tamarack prefers sunny conditions (Proulx et al., 2023). The seedling location relative to the disturbance of a hole or trench on the seismic line was also statistically important. It was determined that seedlings grew at a faster rate when planted closer to the hole or trench. This would suggest that there is no benefit to moving a mound far from the hole on the line, and mounds can be placed directly beside their hole resulting in less planting effort and reduced compression/disturbance on the seismic line. There should be no negative impact if a tree is planted on top of a mound but within close proximity (<30 cm) to the hole or trench on the seismic line. This is a bit different from the results observed for black spruce planted on Inverse mounds. The holes of Inverse mounds filled with water, contributing to mound erosion and subsidence, and resulting in a high percent cover of open water in close proximity to planted seedlings. Under these conditions black spruce growth rates decreased significantly. This is clearly not the case with unfertilized tamarack planted on Inline or Rip and Lift mounds.

5.5.3 How fertilization impacts planted seedling growth and condition

The NPK fertilizer application during planting led to a general increase in growth rates and improvement in seedling condition across both black spruce and tamarack seedlings, with the greatest impact on Unmounded black spruce seedlings. This conclusion is in line with previous peatland studies on these species that have shown increases in seedling height and overall mass after fertilizer application (Mugasha & Pluth, 1994). Fertilizer was expected to increase plant height, since nitrogen, phosphorus and potassium are key nutrients required for photosynthesis and energy production in plants that are often found in low quantities in peatlands (Silfverberg & Moilanen, 2008).

An increase in growth rates was most evident in Unmounded treatments for both black spruce and tamarack and in the Hummock Transfer treatments for tamarack seedlings. The only treatment to have no significant change in growth rate with fertilization was Rip and Lift Mounding. It is well understood that mounding practices increase the availability of nutrients (Londo & Mroz, 2001). When soil is disturbed, there is often an increase in the rate of decomposition, leading to faster nutrient mineralization and an increase in available nutrients (Pearson et al., 2011). Since Unmounded soils were not disturbed, the addition of NPK fertilizer would be the only external source of nutrients to the soil and thus, fertilizer should have a greater impact on the overall seedling growth rates. Mounding treatments like Rip and Lift, Hummock Transfer and Inline Mounding may already have an increased amount of key nutrients available in the soil due to disturbance and the addition of fertilizer may not be as impactful.

Tamarack planted on Hummock Transfer mounds had an increased growth rate with fertilization while black spruce seedlings did not. Since black spruce are more prone to developing multiple leaders, if fertilizer application increased growth across multiple leaders, an increase in overall plant mass would not have been captured in the measurements for plant growth. This potentially explains why some black spruce seedlings did have large increases in height with fertilizer application. A second reason for the interspecies differences may be due to the type of fertilizer applied. The NPK fertilizer prills used in this study have a ratio of 2.5N : 1.3P : 1K. Based on Caisse et al.'s (2008) extensive study of NPK fertilizer ratios on black spruce and tamarack, each species prefers a different ratio of nutrients. Black spruce seedlings see increased growth with greater proportions of nitrogen at a ratio of 4N : 1P : 1.4K, while tamarack have a more balanced optimal ratio of 2.3N : 1P : 1.6K (Caisse et al., 2008). The balanced fertilizer applied in this study is more in line with the optimal proportions for tamarack seedlings. With this fertilizer, black spruce seedlings may not be able to fully benefit from the P and K applications without adequate N. In fact, previous studies on P, K and PK fertilizer applications observed that black spruce saw little to no improvement in growth with K or PK application (Hillman & Takyi, 1998). Applied alone, P fertilizer resulted in a decrease in overall black growth rate (Hillman & Takyi, 1998). Many studies have shown that an increased proportion of N in fertilizer will disproportionately benefit black spruce over tamarack (Mugasha & Pluth, 1994). As a deciduous conifer, tamarack lose N when shedding their needles while the N concentration in black spruce needles increases over time (Mugasha & Pluth, 1994). Therefore, black spruce growth rates may improve to the same extent as tamarack if they are planted with a fertilizer with a higher proportion of N.

In general, seedlings planted on Rip and Lift mounds had above-average growth rates and demonstrate that this types of mound is a suitable environment for black spruce and tamarack seedlings to establish. However, the application of fertilizer did not show noticeable improvements in rates of growth for either species under any growth variables. This may be due to the structure of Rip and Lift mounds. These mounds are made by dragging a ripping shank across the line so the soil folds onto itself to form an area of higher elevation. This disturbance could increase decomposition rates and the availability of key nutrients. In Vodopija's (2021) study, Rip and Lift and Hummock Transfer mounds had the highest rates of decomposition in 2020 than any other treatment at Brazeau. This increase in decomposition may have impacted the way planted seedling reacted to fertilization. The study also found that Inline mounds had the highest decomposition in 2019, so there may be only a one-year increase in soil nutrients due to decomposition rates (Vodopija, 2021).

5.5.4 How fertilization affects the ideal growth conditions of planted seedlings

Similar to unfertilized seedlings, fertilized seedlings prefer elevated and dry soil conditions. When fertilizer was applied, the key relationships with vegetation communities became more generalized as fewer variables were included in the model, but models had higher marginal R^2 values. The relationships between fertilized and unfertilized seedlings also differ between black spruce and tamarack species.

Fertilized black spruce had a positive relationship with soil moisture variables while unfertilized black spruce had a negative relationship with soil moisture. In the LME models of Table 5.3, the soil moisture at the peak is positively correlated meaning that wetter mound peaks improve fertilized seedling growth. This shift in relationships here may indicate that non-traditional mounding is creating water deficient conditions for black spruce or fertilized black spruce are more resilient to wet soil conditions. This pattern may not have emerged in the datasets including Inverse mounds since these mounds had above-average soil moisture conditions. A proposed conclusion is that non-traditional mounds are providing adequately dry spaces for black spruce seedlings to grow. This positive relationship with soil moisture was not seen in any tamarack growth model, suggesting that tamarack growth rates continue to increase with drier mound peaks. Overall, I do not recommend creating wetter mounds to support seedling growth.

Fertilized tamarack seedlings thrive on tall, dry mounds; however, beyond those characteristics they grow best depending on where they are planted on the line. While unfertilized tamarack show no preference, fertilized tamarack prefer to be planted on the edges of narrow lines far from any holes or trenches on the seismic line. Essentially, in areas where they can more easily assimilate back into the forest canopy. In areas where heavy equipment is difficult to transport and targeted planting approaches are being considered, planting fertilized tamarack may be more successful than any other seedling type examined in this study. Regardless, the high areas of the seismic line should still be sufficiently elevated and dry to allow for successful tamarack establishment.

As hypothesized, the relationships with seedlings and surrounding vegetation communities changed with the addition of fertilizer. In fertilized black spruce, the effect of the surrounding vegetation community became more generalized as specific community variables like moss and shrub cover (Table 4.1) were less significant compared with total vegetative cover and the cover of bare soil (Table 5.3). However, the type of community vegetation was less important than the total density of vegetation under fertilization. In this case, both bare soil and vegetative cover were negatively correlated to the growth variables in Table 5.3 and Table 5.4. These results provide conflicting conclusions; showing fertilized black spruce grow best with low cover of bare soil and a low total cover of vegetation. The most plausible conclusion from these results is that fertilized black spruce have higher growth rates with moderate vegetative cover and might benefit from occasional thinning of dense vegetation. One reason this pattern was not observed within unfertilized black spruce may be that the extreme lack of vegetation on Inverse mounds overshadowed these more subtle differences in growth patterns. While lower vegetation density may improve seedling growth, it would not be beneficial to look at Inverse mounding's low vegetation density as an ideal characteristic (section 4.3.2).

Fertilized black spruce were negatively correlated with Sphagnum cover, indicating that seedlings may benefit from some disturbance or removal of Sphagnum moss during restoration. The application of fertilizer in the soil surrounding the tree seedling increases the nutrients available to the surrounding vegetation communities as well. Sphagnum moss in particular is known to be sensitive to fertilizer additions, and can monopolize the uptake of mineral N and P (Sottocornola, Boudreau & Rochefort, 2007). The fertilizer prills in this study were placed in slow-release bags that would provide steady sources of nutrients close to the planted seedling roots. However, when N fertilizer is released into the soil, it could be quickly monopolized by bryophytes like Sphagnum moss (Li & Vitt, 1996). Studies have found that the majority of N additions are found in the top 20 cm of moss in peatlands or at least within the active growing layer of bryophytes (Mugasha & Pluth, 1994; Li & Vitt, 1996). This monopolization helps bryophytes propagate and could hinder tree seedling survival. For this reason, black spruce seedlings, that require greater proportions of N than tamarack, may be disproportionately affected by dense Sphagnum moss when fertilized.

Fertilized tamarack did not show the same relationships with vegetative cover as no vegetation variables were identified as determining factors in seedling growth (Table 5.2). This leads to the conclusion that with the addition of NPK fertilizer, any competitive or mutualistic relationships are overshadowed by the physical characteristics of the mound and planting placement for tamarack. This lack of relationship may be subject to change when the slow-release fertilizers are completely decomposed, and nutrient concentrations return to unfertilized conditions.

5.6 Conclusion

In conclusion, the planted tamarack seedlings grew at much faster rates than black spruce seedlings. This difference has been documented previously and was an expected result of this study. An unexpected result was that tamarack grew as effectively on Unmounded areas of the line as on non-traditional mounds. Since many studies have concluded that any type of mounding is more effective than Unmounded planting to support seedling growth (Filicetti, Cody & Nielsen, 2019), I also hypothesized that this pattern would be apparent in the present study. As tamarack health and growth rates were observed only two years post-planting, further investigation is needed to see if Unmounded planting has a neutral, positive, or negative effect on tamarack growth in the longer term (e.g., 5–10 years). Therefore, my hypothesis was incorrect that Unmounded seedlings would demonstrate reduced growth rates. On the other hand, my hypothesis concerning the ideal growing conditions of unfertilized tamarack was correct, as mound height, soil moisture and sun exposure were important in influencing variation in growth.

Overall, as hypothesized, fertilization generally improved the seedling condition and growth rates of both black spruce and tamarack. Tamarack seedlings were positively affected to a much greater extent in rates of growth and the elimination of dead and unhealthy seedlings. Tamarack seedlings thrived with the application of fertilizer. Black spruce had an increase in growth rates and the reduction of unhealthy seedlings but also had an increased proportion of dead seedlings. Since all fertilized areas were located on the Brazeau South line and the sample size of fertilized trees was smaller, specific local conditions (e.g., hydrology, plant community) may have disproportionately affected this dataset. My hypothesis that fertilizer would improve seedling growth was correct for all mounding treatments except Rip and Lift. Further investigation into Rip and Lift mounds is needed to identify the exact reasons why fertilizer was less effective with this treatment.

Finally, my hypothesis that fertilization would reduce vegetation competition was correct for tamarack seedlings but not for black spruce. It seems that black spruce seedlings struggled to compete with surrounding bryophytes for the NPK nutrients in the fertilizer. Conversely, fertilizing tamarack seedlings eliminated vegetation communities as limiting or supporting factors, as they were all eliminated from statistical model results. Overall, fertilization improved the health and growth rates of tamarack more than those of black spruce.

Chapter 6 – Implications for seismic line restoration projects

As seismic lines continue to be created and legacy lines show little recovery after their initial disturbance, restoration activities are a necessary solution to protect Alberta's boreal treed peatlands. Prioritizing sites is important as hundreds of thousands of seismic lines remain open in Alberta, making it cost prohibitive to restore them all (Dabros et al., 2017). Restoration plans at the landscape level need to be selective; the selection criteria could include regional divides, line age, line width, species at risk habitat or other factors of expected restoration success (Government of Alberta, 2018). An effective restoration plan needs to be focused, actionable and measurable for specific goals since peatland ecosystems are complex and provide multiple key services and opportunities for human-nature interactions (Government of Alberta, 2018). In this chapter, I will provide four suggestions to inform restoration plans based on the results of this study. This includes: (1) choosing a mounding practice proven to produce ideal seedling growing conditions; (2) considering alternatives to mounding, when mounding is unrealistic or not cost-effective; (3) developing a method to reduce seismic line disturbance from human traffic; and (4) identifying effective monitoring practices.

6.1 Choosing a mounding method

There was no mounding method that unilaterally supported fast-growing trees regardless of species and fertilization. There was an indication that Rip and Lift and Hummock Transfer methods supported increased growth during certain growing seasons, but not biennially. Therefore, to identify an optimal mounding method, it is best to use the ideal growth conditions identified in the statistical models. The seedlings observed in this study grew at a faster rate when they were planted on narrow seismic lines and tall, dry mounds with high tree and forb cover, but otherwise moderate vegetation community cover. In this study, moderate cover of other vegetative communities refers to the lower quartiles (i.e., 50-75% bryophytes, 5-15% graminoids, 5-10% shrubs; Table 3.3) of Unmounded or non-traditional mound surveys. Statistical models including Inverse mounds had a positive relationship between growth and all vegetative covers, but models without Inverse mounds had both positive and negative relationships. The low vegetation density on Inverse mounds skewed the relationships between seedling growth and vegetation cover and obscured the negative correlation between select vegetation communities and seedling growth on non-traditional mounds. Overall, the average vegetative cover recorded on Inverse mounds is too low to encourage tree seedling growth.

Since trees grow the fastest on narrow seismic lines, restoration plans may consider creating separate planting methodologies depending on line width. For example, this could include prioritizing narrow lines for quick landscape level recovery, or prioritizing monitoring resources for wide lines to support adaptive management. To evaluate line width at a landscape level, the Forest Line Mapper is an excellent software tool to accurately identify line location, length, and width (Queiroz et al., 2020). This semi-automatic mapping software can provide information to help identify the exact locations and sizes of seismic lines, thereby helping identify lines with the characteristics that are best suited to a particular restoration method.

Trees prefer tall, dry mounds; Rip and Lift and Hummock Transfer mounds were both above average in these categories, with an average height of 18 cm, an upper mound elevation range of 23 cm to 30 cm and a maximum height of 50 cm. Inverse mounds had the highest mound elevation out of any mound type, but they experienced severe slumping and/or erosion that likely reduced the average mound height by ~70%, to a level not significantly taller than non-traditional mounds. Since Inverse mound soils had the greatest soil moisture content of any mound type, it is evident that this mounding methodology does not provide a tall or dry space for seedling roots. When building Inverse mounds large holes are left on the seismic line and become pools of standing water. These areas will likely remain largely unvegetated and act as methane hotspots (Schmidt et al., 2022). In addition, the level of disturbance caused by Inverse mounding is high and has negative implications for the integrity of peatland ecosystems. Overall, it is clear that the cost and labour of Inverse mounding, alongside its detrimental effects on ecosystem services, make it an unsuitable option for robust restoration plans.

High density of tree and forb vegetative cover were identified as mound characteristics that support fast seedling growth. However, there is no single mound type that exemplifies both of these characteristics. Inline and Inverse mounds had high tree cover while Unmounded and Rip and Lift mounds had high forb cover. Another ideal vegetative characteristic was having high total vegetation cover but below-average vegetative density of specific community types. For example, Unmounded and Hummock Transfer mounds had low Sphagnum cover without having low total vegetation cover. With these competing factors in mind, Inverse mounds were disqualified as ideal due to low total vegetation cover and Unmounded areas for having low tree density, but one non-traditional mounding method cannot be identified as superior based solely on vegetation percent cover.

The mounding methods that best supported generalized tree growth were Rip and Lift and Hummock Transfer mounding due to their tall, dry mounds. The final consideration in choosing between these two mounding methods is the cost effectiveness of the labour required for each methodology. Rip and Lift mounds are simple to create and cause limited disturbance to the landscape as they leave deep but narrow holes on the seismic lines. Hummock Transfer mounding is time consuming as a technician must find a viable mound from the natural area to transplant onto the seismic line. This also redistributes the disturbance to a wider area by impacting peatland areas that were not initially disturbed. With this in mind, I recommend Rip and Lift mounds for further study and consideration in peatland seismic line restoration plans.

6.2 Unmounded planting approaches

There was no strong evidence that suggested trees planted on Unmounded lines had significantly lower or higher rates of growth than any non-traditional mounding method. In fact, fertilized black spruce trees had the highest rates of growth and lowest proportion of death in Unmounded areas. This study found that Unmounded planting, (or plant-as-is), is as successful as non-traditional mounding in the initial two years of seedling survival and growth.

Successful unmounded planting could be an exciting alternative restoration method for seismic lines as it eliminates the need for heavy equipment. Running heavy equipment for MSP and mounding causes further disturbance to seismic lines that ideally should be avoided. In addition, equipment and qualified technicians are expensive and difficult to transport. This is especially true in remote regions with fly-in only access. Not all seismic lines are fully clear for transport, it may not be possible to drive heavy equipment across an entire line if seismic lines were previously stem bended, blocked by fallen trees, overgrown with woody vegetation or developed into other human land uses. It is more feasible to transport personnel and tree seedlings via helicopter for unmounded planting methodologies in remote regions. Therefore, the measured success of unmounded planting opens up new landscape restoration opportunities that otherwise would be inefficient.

To prioritize peatland seismic line restoration using unmounded planting approaches, it is important to choose sections of seismic line with a moderate to high level of microtopographical variance. The Unmounded areas in this study had a microtopographical variance similar to non-traditional mounds. It is unknown if seedlings would have survived and grown well if the Unmounded area had lower variance. Therefore, results suggest that unmounded planting methods could be successful on seismic lines with above average microtopographical variance. In Stevenson, Filicetti & Neilson's (2019) recent and extensive survey of microtopographical reduction on seismic lines, the average reduction was 20%. I recommend choosing narrow seismic lines with under 20% microtopographical reduction, with seedlings planted on local high elevation areas as a suitable test for unmounded planting methods.

6.3 Effective strategies to reduce traffic on seismic lines

Boreal peatland seismic lines are sensitive to disturbance and have very slow natural rates of recovery (Hornseth et al., 2018). If seismic lines are continually disturbed, they will not be able to achieve ecosystem recovery. Continual disturbance, especially from motorized vehicle traffic can worsen seismic line conditions as they further compact peat soils, destroy new vegetation, and disturb the top layers of soil (Pigeon et al., 2016). Seismic lines are often used as a passage for easy transportation by wildlife, humans, and vehicles alike; their use as a trail is closely related to their flat topography and lack of tall vegetation (Pigeon et al., 2016). To discourage heavy traffic on seismic lines, some strategies to consider are roughening the topography, blocking accessible areas, and introducing tall vegetation as quickly as possible.

To roughen seismic line topography, mounding is an excellent option since it can serve a dual purpose of increasing variance in microtopography and providing ideal habitat for planted tree seedlings. In this study, Rip and Lift, Hummock Transfer and Inverse mounds had the highest average mound heights. To avoid causing further disturbance to the seismic line I would disqualify Inverse mounding as an acceptable choice. I recommend Hummock Transfer mounds as the ideal choice to prevent traffic because they are easier to see than Rip and Lift mounds during the initial years post-mounding. Since these mounds are transplanted with their existing vegetation, they retain some height from existing shrubs and trees in their first growing season and may limit human traffic immediately after transplanting. To save labour costs and reduce disturbance to untouched areas off the seismic line, Hummock Transfer could be employed within only the first 200 m of the entrance into a seismic line. Another non-traditional mounding method, like Rip and Lift or Inline Mounding, could be used on the rest of the line. A physical barrier may also limit human and vehicle traffic on seismic lines. Using high density stem bending at the entrance of trafficked seismic lines is my recommendation. By creating an unwelcome space for movement with obstacles and a high variance in microtopography, restoration plans could reduce the likelihood of chronic disturbance on seismic lines.

In addition to roughening topography and creating barriers, a high density of tall trees is an effective method of reducing traffic on seismic lines (Filicetti, Cody & Nielsen, 2019). Planting a quick growing species is a possible strategy to increase canopy density. Based on the results of this study, fertilized tamarack planted on Hummock Transfer mounds had the highest rates of growth. Though other non-traditional mounds demonstrated similar growth rates. Therefore, it is my recommendation that fertilized tamarack be planted on seismic lines known to suffer from continuous disturbance due to human traffic. It must be noted that while fertilization improves seedling growth, it can have other negative impacts to the ecosystem. For example, the application of fertilizer is known to decrease water quality as nutrients leach into groundwater and can spread to other regions as sub-surface flow (Piirainen et al., 2013). In addition, fertilizer has been linked to the encroachment of invasive species and may allow graminoids or deciduous trees to outcompete native species in boreal peatlands (Nishimura & Tsuyuzaki, 2015). A shift in species composition away from native mosses may also limit the peatland’s ability to sequester carbon and continue peat formation (Urbina & Benavides, 2015). Therefore, a site-specific risk assessment should be undertaken prior to fertilizer application and/or fertilization should be limited to small areas.

6.4 Monitoring restoration efforts

A key aspect of any robust restoration plan is monitoring. Without monitoring, we have no way of evaluating the effectiveness of restoration. This study evaluated both restoration methodologies and the characteristics of mounds and seedling growth in an effort to identify successful strategies for restoration and monitoring. Through statistical analysis, I identified the most repeated effects across models as either limiting or supporting factors for tree growth. The key factors were mound height, mound soil moisture, tree cover and forb cover surrounding the planted seedling. Monitoring efforts need to be representative of their restoration plan. For small restoration projects, it may be feasible to evaluate all four of these key effects at the site level. Soil moisture for example, is difficult to accurately measure quickly across an entire site, therefore it may be feasible to measure in small, local or important sites. For restoration completed at a landscape level, alternative methods of data collection are needed to monitor in an efficient fashion. Mound height, or more accurately, the variance in site microtopography can be measured precisely and quickly using remote sensing tools such as unmanned aerial vehicles (Lovitt et al., 2017). Measuring surrounding vegetation communities can be conducted using smartphone technology (or aerial photography) as evidenced by Davidson et al.'s (2021) study on peak greenness. Using smartphone photographs or potentially using drone photography or satellite photography, it is possible to identify surrounding vegetation by their greenness. In boreal forested peatlands, many trees are evergreen conifers and an evaluation of peak greenness in the late fall or early spring may indicate the proportion of trees growing on a seismic line. The proportion of forb species may also be indicated through the change in greenness before and after forb species have grown each spring. Through these methodologies, it may be possible to provide methods of efficient monitoring at landscape scales during the post-planting phases of a seismic line restoration plan.

6.5 Conclusion

This study was the first to compare multiple non-traditional mounding techniques, Inverse Mounding, Unmounded areas and Natural areas for micro-ecosystem characteristics relating to black spruce and tamarack seedling establishment and growth. The study of two conifer species, black spruce and tamarack, and the use of fertilized and unfertilized planting sections provided an examination of the most common methods of tree regeneration in Alberta's boreal forested peatlands. Through this study, I identified how physical variation in mound size, mound soil moisture, key vegetation communities and fertilization impact seedling growth two years post-planting. This information provides new insight into understanding how different mounding methodologies can create an optimal microsite for conifer seedlings. While mounding can improve seedling health and overall condition, seedlings were shown to have a high rate of survival on unmounded areas of seismic lines. Hence, unmounded planting cannot be disregarded as a restoration technique. In addition, this study proved that traditional mounding or 'Inverse' mounding did not provide an advantage over non-traditional mounding techniques, nor do Inverse mounds sustain the ideal growth characteristics for seedlings. It was demonstrated that non-traditional mounding methods are more capable of supporting seedlings within the first two years of planting. There is still much to study about mounding in peatlands. In particular, further study on Rip and Lift mounds is required to fully understand their unique soil structure and its effect on soil characteristics like carbon cycling and potential GHG emissions due to soil disturbance. Further study on how mounding methods affect tree growth in the long-term is also needed. Revisiting these five planting methodologies with seedlings at five, ten or more years post-planting would also provide a greater understanding of how mounding affects seedlings long term and the impact on the return of the forest canopy.

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Appendix A: Seedling sample size at each plot

Table A: Summary of seedling sample size and survival rate by treatment plot.

Treatment Plot	Estimated black spruce planted	Black spruce observed	Black spruce survival (%)	Estimated tamarack planted	Tamarack observed	Tamarack survival (%)	Total estimated planted	Total observed	Total survival (%)
Natural	n/a	66	n/a	n/a	24	n/a	n/a	90	n/a
Plot 15: Brazeau Poor Fen*	n/a	30	n/a	n/a	0	n/a	n/a	30	n/a
Plot 16: Brazeau Rich Fen	n/a	6	n/a	n/a	24	n/a	n/a	30	n/a
Plot 18: LLB North Natural**	n/a	15	n/a	n/a	0	n/a	n/a	15	n/a
Plot 20: LLB South Natural**	n/a	15	n/a	n/a	0	n/a	n/a	15	n/a
Unmounded	120	81	68 to 76***	120	92	77 to 85***	240	173	72 to 80***
Plot 13: Brazeau North	40	32	80	40	40	100	80	72	90
Plot 14: Brazeau West	40	10	25 to 50***	40	10	25 to 50***	80	20	25 to 50***
Plot 12-1: Brazeau South Unfertilized	20	21	105	20	22	110	40	43	108
Plot 12-2: Brazeau South Fertilized	20	18	90	20	20	100	40	38	95
Rip and Lift	310	256	83	310	280	90	620	536	86
Plot 3: Brazeau North	150	139	93	150	143	95	300	282	94
Plot 4: Brazeau West	60	30	50	60	37	62	120	67	56
Plot 11-1: Brazeau South Unfertilized	50	52	104	50	58	116	100	110	110
Plot 11-2: Brazeau South Fertilized	50	35	70	50	42	84	100	77	77
Hummock Transfer	210	149	71 to 88***	210	160	76 to 92***	420	309	74 to 90***
Plot 2: Brazeau North	75	58	77	75	68	91	150	126	84
Plot 6: Brazeau West	75	35	47 to 93***	75	34	45 to 91***	150	69	46 to 92***
Plot 9-1: Brazeau South Unfertilized	30	23	77	30	22	73	60	45	75
Plot 9-2: Brazeau South Fertilized	30	33	110	30	36	120	60	69	115
Inline Mounding	210	148	70 to 88***	210	140	67 to 83***	420	288	69 to 85***
Plot 1: Brazeau North	75	34	45	75	43	57	150	77	51
Plot 7: Brazeau West	75	36	48 to 96***	75	35	47 to 93***	150	71	47 to 95***
Plot 10-1: Brazeau South Unfertilized	30	51	170	30	37	123	60	88	147
Plot 10-2: Brazeau South Fertilized	30	27	90	30	25	83	60	52	87
Inverse Mounding	n/a	139	n/a	0	0	n/a	n/a	139	n/a
Plot 17: LLB North	n/a	64	n/a	0	0	n/a	n/a	64	n/a
Plot 19: LLB South	n/a	75	n/a	0	0	n/a	n/a	75	n/a

* Fewer small Tamarack trees observed around Plot 15, none observed on transect

**Natural Tamarack present along transect but excluded since Tamarack was not planted on LLB Study Sites

*** Estimated survival rates given that only half the plot was measured for Plots 6, 7 and 14, new values double observed seedling counts to create an estimated survival range

Appendix B: WET Sensor Calibration

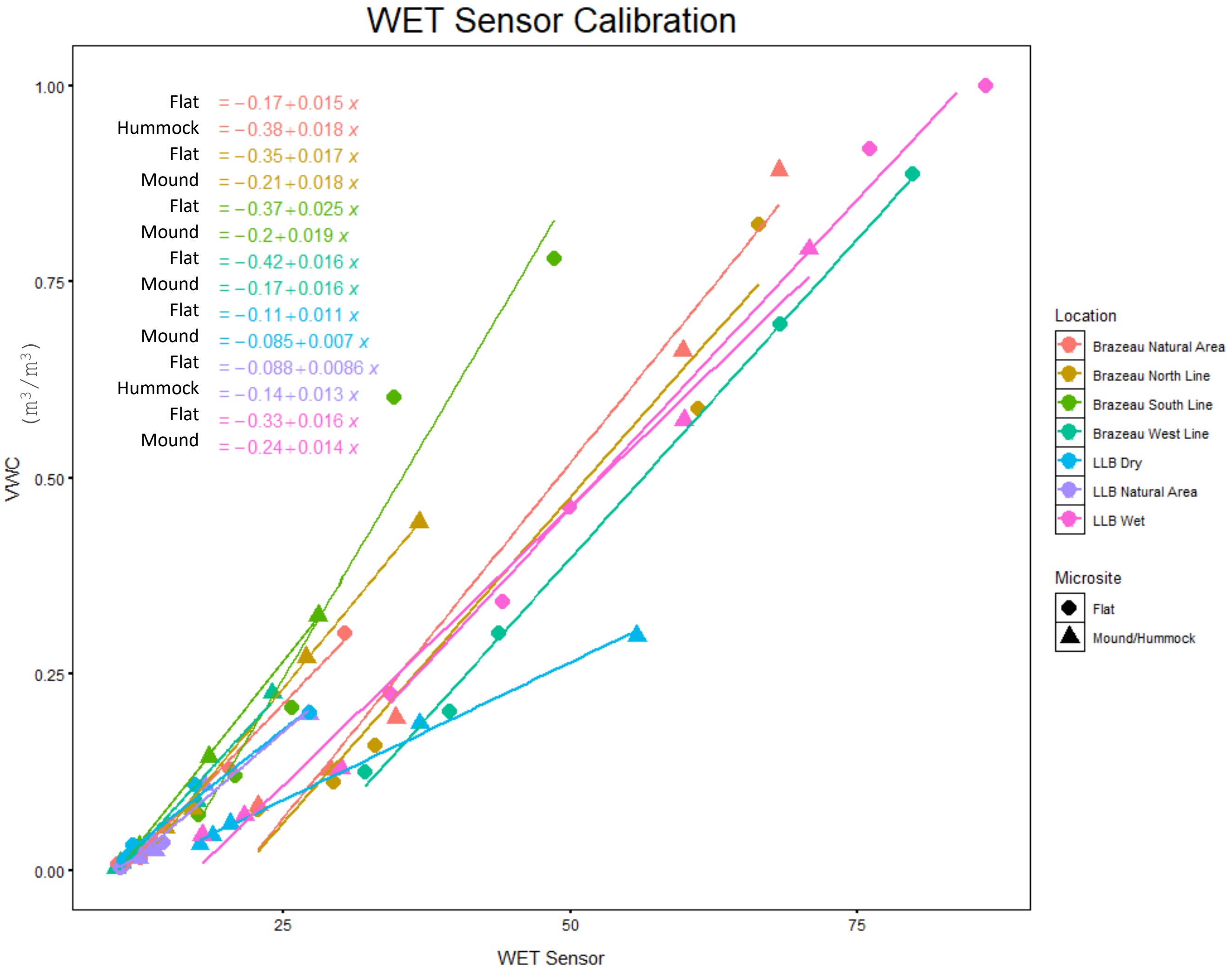

*Figure B: WET-sensor calibration curves for representative soil samples. Calculated volumetric water content (m^3/m^3) plotted against WET-sensor measurements. Calibrations were made according to closest location and microsite elevation. Mound peak and tree soil moistures were calibrated with 'Mound/Hummock' values. Seismic line flat soil moistures were calibrated with 'Flat' values. ***All calibration curves had an R^2 value >0.9*