THE EFFECTS DIFFERENT COMMERCIAL THINNING TREATMENTS HAVE ON BLACK SPRUCE (*PICEA MARIANA*) DIAMETER, BASAL AREA, HEIGHT AND VOLUME

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April, 2023

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An Undergraduate Thesis Submitted in Partial Fulfilment of the Requirements for the Degree

of Honours Bachelor of Science in Forestry

Faculty of Natural Resource Management

Lakehead University

April 2023

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Douglas Reid, Major Advisor Dr. Wang, Second Reader

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ABSTRACT

Maxfield, D. 2023. The effects different commercial thinning treatments have on black spruce diameter, height, basal area and volume. Lakehead University pp. 45

Keywords: Chapman Richards, Commercial thinning, Basal Area, DBH, Volume, Honers

Commercial thinning is a potential opportunity for forest managers to realize mid rotation wood volume while stimulating increased growth of residual trees for the final harvest. The practice of commercial thinning is, however, not a common practice in Ontario due to lack of experience and scientific evidence. This thesis evaluates the effects of four different thinning treatments on two different black spruce (*Picea Mariana*) boreal forest sites10 years following commercial thinning. The four treatments were analyzed from a commercial thinning operational study conducted in northwestern Ontario in 2007. Analysis included; diameter at breast height (DBH), basal area, height and volume. Two factor ANOVA tests indicated significant effects of treatment or treatment by site interactions showed direct and strong evidence that the thinning treatments had effects. Significant site effects from the ANOVA tests also tells us that there is a difference in the variables we measured between sites. Commercial thinning does show promise and these legacy sites are a unique research opportunity deserved of ongoing study to further understand the treatment effect thru to final rotation age.

ACKNOWLEDGEMENTS

I want to express my gratitude to everyone who has assisted me in finishing my thesis experiment over the past five months. I want to start by thanking three of my former professors, Jian Wang, Dzhamal Amizhev, and Steven Hart, who have helped me learn everything I know about silviculture today. Most of all, I want to express my gratitude to Dr. Douglas Reid of the Ontario Ministry of Natural Resources' (OMNR) Centre for Northern Forest Ecosystem Research (CNFER) for personally driving me to the limestone plantation site, helping me with research and writing, providing the data, helping with statistical modeling, and reviewing my thesis. I also like to thank the CNFER technicians who measured the trees and generated the information needed for this investigation.

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INTRODUCTION

Black spruce is one of the most important boreal tree species in Canada. It is a wide-ranging conifer that is abundant throughout the northern areas of the North American Boreal Forest. Black spruce is a moderately shade tolerant species that can grow slowly but is capable of producing some of the highest quality fibers within the pulp and paper industry. "In the current ecosystem-based management context, commercial thinning (CT) could be a sound choice for attaining sustainable forest management while still achieving maximum returns on competitive timber markets (Vincent et al. 2009)". Thinning reduces the basal area within a stand to help alleviate competition and create more resources and favour growth of the trees left in the stand. Commercial thinning is applied as an effective means to extract timber in the short term by selecting stems approaching imminent natural mortality. "The long-term goal is generally to increase the growth of residual trees following thinning by decreasing the competition for available environmental resources (primarily light, nutrients, and water) (Kostler 1956; Zeide 2001)". This potential for increased growth long term is strong incentive for forest managers striving to increase fiber supply.

A mid-rotation commercial thinning experiment was conducted in 2007 at the Limestone Lake plantation. These plantations are primarily composed of black spruce and are located in Northern Ontario roughly 20 km north of Nipigon, ON on two sites 1) Boom Site and 2) Airstrip Site and were analyzed for differences of a variety of growth responses 10 years after four levels of CT. These sites slightly differ slightly in terms of soils but are both for the most part pure black spruce. Treatments included four levels of thinning intensity; Light thin (LT) Moderate thin (MT), Heavy thin (HT) and Quality thin (QT), and Untreated controls (C). Within each plot, heights and diameters were measured on a subset of black spruce trees. This experiment was established by the boreal silviculture research program at the Centre for Northern Forest Ecosystem Research (CNFER). CNFER owns the data used for this experiment as they were responsible for surveying and subdivided the stands into 1 hectare treatment plots and collecting data in 2007 (Year 0), 2012 (Year 5), and 2017 (Year 10). All data was collected from permanent growth plots established in each of the treated stands, including un-thinned controls. This experiment was established by the boreal silviculture research program at CNFER. Airstrip site black spruce trees were planted in 1961 and Boom site trees in 1960. This experiment will help determine which of the four levels of commercial thinning treatment were most successful for the increase of height, diameter at breast height (DBH), and tree volume in mid-rotation black spruce plantations.

The objective of this thesis was to evaluate the effects that 4 different thinning treatments have on two different sites of black spruce 10 years after the commercial thinning treatment. Data used to develop this thesis comes from an experiment designed to evaluate the viability of commercial thinning in mid rotation managed black spruce stands in Ontario. Suitable stands for this treatment are mainly pure black spruce and are typically established as plantations. This paper will examine the difference between the four treatments and record any variances between the two different sites of Airstrip and Boom regarding to the different response variables. The response variables analyzed at both sites include; diameter at breast height (DBH), height, basal area and total volume. There is a lack of experience and scientific evidence to support commercial thinning of black spruce stands in Ontario. Understanding the effects of each treatment on different sites can assist forest managers in making future decisions in accordance with their specific forest management objectives. These stands are some of Ontario’s oldest, most intensively managed upland spruce plantations, effectively making them excellent research locations.

1.1 - Commercial Thinning

Forest managers must implement a specific silvicultural system that is suited best for a particular stand and achieves certain management objectives. Among the different silvicultural systems, thinning has been a popular approach for influencing stand growth, yields, products, and biodiversity. Trees compete for a fixed amount of light, moisture, and nutrients. “Forest ecosystems have a natural carrying capacity and can sustain only a finite number of trees and vegetation. As seedlings grow bigger, they begin to compete with one another for the resources they need to survive, resulting in some trees dying off (Northwest Natural Resource Group 2017)”. When a stand is thinned, stem stress is alleviated by decreasing the amount of competition for all the remaining trees left within the stand and, therefore, increasing the availability of nutrients to produce healthier more productive trees. Commercial thinning is often applied as an effective means to extract timber in the short term by selecting stems approaching imminent natural mortality. After a thinning operation, it is expected that the individual trees and overall stand-level growth will be improved as there are more environmental resources such as growing space, light, water, and nutrients available to fewer trees.

Commercial thinning requires the thinning of mature trees within a stand at mid-rotation instead of young seedlings as in pre-commercial thinning. The main difference between pre-commercial thinning and commercial thinning is the timing of the thinning. Trees removed as part of a pre-commercial thinning (PCT) treatment are lack size and maturity and are without commercial value whereas commercially thinned (CT) trees approaching maturity do have commercial value. In commercial thinning the objective is to create room in the stand for the remaining residual trees so they have the capacity to grow, gaining volume that would otherwise be lost to mortality or competitive stress. Other types of commercial thinning include thinning from above, thinning from below, or free thinning. Thinning from above, thinning below and free thinning are prescriptions applied by forest managers to help forest operators decide on which of the trees will be removed. When thinning from below, small trees in the stand are cut and removed, while the larger trees remain in the stand. This method favours the taller trees in the stand by removing the lower crown classes. Thinning from above is the opposite as it involves the removal of the larger trees and leaving the smaller trees to grow, the removal of trees in the middle and upper crown classes to favour the best dominant and co-dominant species (Government of British Columbia 1999). Free thinning occurs when you are thinning under specific criteria. These are prescriptions where the operator has different targets so in some tree species such as Norway spruce, more shade tolerant thinning from above is practised. This is where the bigger trees in the stand are removed, leaving the smaller ones. The basic if this thinning treatment is to choose tress with enough tree crown to be able to respond. This practice does not work when dealing with shade intolerant stands as the smaller shade intolerant trees in the understory, with smaller tree crowns, cannot take advantage of the new growing space. CT works well with shade tolerant species as they are capable of maintaining large crowns even though they are in a sub dominant position and can grow quickly once their growth response is stimulated from the new growing space post thinning.

Depending on the location and the forest tenure rules, CT can be a great treatment to establish a higher quality stand. According to "(Nova Scotia Canada 2022) the intent of CT operations is to generate immediate economic benefit, increased future value, and improved health and vigour of the forest stand". The government of "(Nova Scotia Canada 2022) also noted that CT's involve cutting trees that have reached diameters that can be processed and sold as doing this will bring immediate revenue and improve future economic value of the stand". Some of the other potential benefits from using commercial thinning treatments with black spruce includes; improving quality and value of trees left in the stand; reducing future harvesting costs; harvesting valuable trees that might otherwise be lost to mortality; and providing employment opportunities mid-way through a harvest cycle.

In a natural stand, operators commonly waste time and money dealing with non-merchantable wood in order to access the merchantable wood. During the final harvest in a previously commercially thinned stand, however, every single stem harvested will most likely have merchantable value. Managers must decide whether commercial thinning is really feasible, as they are the ones responsible for the added cost of commercially thinning a mid-rotation stand rather than leaving it to harvest at normal rotation age. Forest managers must decide whether the higher value timber at rotation is justified by the cost benefit associated with a mid-rotation commercial thinning. Countries where commercial thinning is widely practised are generally where forest companies have permanent tenure over the forest management land base (ie: private land) where the trees are utilized by the company when the time comes for final harvest. In Canada, the tenure over the land is not as secure (ie: Crown land) and can be licensed to different companies throughout the lifespan of a tree stand. This can only be accomplished when the new forest tenure owner follows a contract which may require specific volumes to be produced at certain times. Forest tenure for blocks of land are not very secure or guaranteed for the full life span of a tree in Canada, and this has had a large influence on the Canadian forest industry when deciding to carry out commercial thinning operations.

1.2 - Growth Responses to Thinning

Thinning is an important silvicultural technique which is applied to forest stands with the intention of increasing growth responses resulting in a higher quality wood product. Thinning not only removes trees, but changes the environmental conditions, which are then applied to meet various forest-management objectives (Zeide 2004). When comparing growth to yield of a tree, we are using a more economic approach as yield is simply the merchantable volume of a tree. "Merchantable tree volume is total tree volume minus the volume of the stump and top (Nigh 2016)". While most people tend to focus on overall growth of a tree or forest, forest companies are focused on the economic opportunity and are primarily interested in merchantable yield of tree. A growth and yield model assists foresters when making predictions on the relationship between certain characteristics of a stand and the growth and yield of the tree species within it. "Growth and yield predictions are used to update forest inventories, provide input for forest management planning, evaluate stand management opportunities, and assess the impact of pests and fire on timber yield (Tomson 1991, p. 2)". The objectives for forest management can often be achieved by controlling the characteristics within a forest stand as this will influence the growth and yield of those stands.

Thinning treatments will most likely result in different values in-regards to overall quality and economic value. The government of British Columbia has provided some guidelines on timing of CT (Government of British Columbia 1999). They include; 1) commercial thinning traditionally is carried out during the active height growth period of a stand to foster a growth response in the remaining trees; 2) traditional commercial thinning is done prior to culmination of mean annual increment (MAI) (stand age ranging from 30–60 years, depending on growth potential); and 3) an older stand where height growth of the dominant and codominant trees is already slow (i.e., flat portion of height/age curve past culmination of MAI), there will not likely be a growth response to thinning.

There have been other studies done in the past throughout Canada and the world for analyzing the effects of tree level growth following commercial thinning operations. A study in New Brunswick was carried out by Pelletier (Pelletier et al. 2008) to analyze silviculture responses of spruce plantations to commercial thinning. They discovered that all of the thinning treatments applied were able to satisfy their objectives of increasing diameter and volume growth on a reduced number of stems (Pelletier et al. 2008). Early thinning operations increased mean diameter and mean merchantable volume per stem at the end of the observation period compared to the un-thinned stands (Pelletier et al. 2008). Another study was conducted by (Tong et al. 2011) in Kapuskasing, ON where they analyzed the impact of CT on annual radial growth and wood density in plantation grown black spruce. They were able to determine that heavy CT had a significantly positive effect on annual radial growth within plantation-grown black spruce blocks (Tong et al. 2011). The effect of thinning on ring width and density depended on tree diameter and height position. Heavier thinning intensities in general are more effective on annual growth (Guller 2007), this is because of the increased amount of carbohydrate produced by a tree due to the increased growing space for roots and crowns of residual trees (Smith et al. 1996). Another study was conducted throughout the USA analyzing tree level growth of numerous tree species following commercial thinning (Bose et al. 2018). The results from their study indicated that commercial thinning treatments were effective in increasing the volume growth and probability of survival of residual trees across four commercially important softwood species of North America. The species included in their study (Bose et al. 2018) were loblolly pine (*Pinus taeda*), Douglas fir (*Pseudotsuga menziesii*), red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*). It was discovered that on average, tree volume growth was 31% higher in thinned stands relative to un thinned stands irrespective of species and tree size (Bose et al. 2018). In-regards to the effects CT has on basal area, a study was done on basal area development within thinned and un-thinned loblolly pine plantations by (Hasenauer et al. 1997) who determined that there is no evidence that the basal area of thinned plots will exceed plots that are un-thinned. Under thinning intensities which remove more basal area, the likelihood of basal area convergence between thinned stands and an un-thinned stand decreases. They confirmed within their study that thinning does not increase total stand basal area (Hasenauer et al. 1997).

Any commercial thinning of such stands should have clearly set objectives. The most common objectives for a CT operation include improving timber quality and yields of residual overstory trees (Zeide 2004), reducing ladder fuels to decrease the potential damage from wildfires, increasing vigor within the tree to curtail beetle infestations (Sorensen et al. 2011, Hood et al. 2016), and promoting drought resilience (D'Amato et al. 2013). "Late thinning may be considered in stands where it is desirable to significantly extend the rotation in order to achieve specific management objectives (Government of British Columbia 1999)". Commercial thinning affords the opportunity for forest managers to realize merchantable volume, mid-rotation, for commercial benefit. A good commercial thinning operation may also positively affect the stand growth and quality for the future final harvest. One of the advantages of commercial thinning is that the two-stage harvest can potentially realize more total merchantable yield from a stand than you would normally get from one harvest at the final rotation age. However, that yield does come at a cost as pulling the wood out during a commercial thinning operation takes time and costs money. Managers need to make important economic decisions regarding as to when the thinning should occur and when the best time to harvest the stand is in order to extract the most yield possible with the most economic benefit. "The timing of the commercial thinning, relative to the age of the stand, affects the volume and value of the final stand (Government of British Columbia 1999)".

1.3 - Eco-Physiological Effects of Thinning

Trees grow by absorbing carbon dioxide (CO2) out of the atmosphere, releasing oxygen by way of photosynthesis, and storing carbon in their trunks. "When the leaves land on the ground, soil microbes work to decompose the leaves and other organic matter, which releases carbon dioxide (Collarossi 2022)". Photosynthesis is when a plant or tree absorbs sunlight, water and carbon dioxide from their microsite environment to establish oxygen for the atmosphere and energy for the organism. Plants absorb carbon dioxide (CO_2) and water (H_2O) from the air and soil during photosynthesis. Within a plant cell, water is oxidized and carbon dioxide is reduced. This process will transform water into oxygen and transform carbon dioxide into glucose. Glucose is very important for trees as it is used for energy and to make other substances like cellulose. Cellulose is the most important polysaccharide present in plants as it is involved with building new cell walls. Plants use cellulose to make their stems, branches and leaves strong. Not only does commercial thinning enhance the growth and yield of a stand for higher future value, but it also enhances ecosystems. "Some of the ecosystems enhancements from thinning operations include; decreasing soil respiration at a given temperature (Tang et al. 2005) and modifying water quantity (Molina and del Campo 2012)". In order to evaluate the effects of different thinning treatments your results must be compared to the control sites (un-thinned sites), as this allows you to measure the thinning response variables between the thinned sites and those with no thinning.

Not only was CNFER analyzing different growth responses for the black spruce within each of the experimental blocks but they were also analyzing the physiological responses. Some of the physiological responses examined included the sap flow and transpiration of the trees within the different thinning treatments. "Black spruce trees growing in nutrient-poor permafrost peat soils were found to have lower mean sap flux density than those growing in mineral soils (Warren et al. 2018)". These physiological responses created from the different thinning intensities were examined while also monitoring changes in weather/climate conditions like temperature, humidity, wind speed, and light. "Thinning as a management tool affects tree cover and in turn influences soil processes, especially soil moisture (SM) (Del campo 2022)". Black spruce is most productive in terms of growth when residing on sites that are moist. Many studies have shown that thinning increased the transpiration and stomatal conductance on foliage of residual trees. “Transpiration is water loss associated with evaporation from within the leaf whereas stomatal conductance is the conductance of $CO2$ or water through the stomata (Lambers *et al.* 2006)”. According to a global review paper done by (Del campo, 2022), who analysed a total of 251 observations from 57 peer-reviewed publications which were compiled for the different key ecohydrological processes of canopy and soil moisture. it was discovered that when you thin a stand you are not only affecting the growth from having less competition but are also affecting the ecohydrological processes. “Thinning enhances runoff and groundwater recharge and mitigates the effects of drought through increasing Water use Efficiency (Del campo 2022)”. Soil moisture and tree-level water use increase after thinning compared to the control. Thinning intensities that reach about 50% basal area removal are considered a threshold where hydrological processes are significantly affected. Black spruce trees within the highest intensity treatment (HT) at the Limestone Plantation, are likely to have had their hydrological processes significantly affected due to increased soil moisture.

When conducting a thinning treatment, the density of a tree stand is reduced in order to stimulate growth responses from those trees remaining within that stand. It is important to recognize that thinning treatments are not without risk. Thinning decreases the density of a stand and can potentially increase the risk of blowdown and breakage, making the trees more vulnerable to mortality. Trees left within the newly thinned stand become more vulnerable to wind and heat damage. “Trees have been observed to acclimate to new wind regimes within a few years after thinning and exposed trees achieve this by allocating a greater proportion of available biomass to the stem base and below-ground (Nicoll et al. 2019)”. Thinning of any kind is an uncommon practice when it comes to black spruce as there are many other faster growing softwood species found in the boreal forest. Thinning black spruce in some provinces is yet to be a recommended practice due to the lack of information. However, as of late, black spruce has received an increased amount of attention and commercial thinning is gradually a more important practice. Black spruce grows slowly compared to other softwood species and because of this some forest management companies find themselves planting faster growing species like red and Norway spruce (*Picea abies*). The faster the trees can grow into quality lumber the sooner forest companies get a return for their investment in thinning and other silvicultural treatments. However, black spruce from the boreal forest is widely recognized to have higher value than many faster growing species due to its long and strong fibres, excellent for paper products. Canada and Northern Ontario has tremendous capacity for growing black spruce due to the expansive public forest landbase, the soils and the climate.

1.4 - Background on the Limestone Lake Plantation

The Limestone Lake Plantation was established under the supervision of George Marek, a forester who worked for the Ministry of Natural Resources at the time. According to George’s obituary (George Marek Obituary (2003) - Thunder Bay Chronicle Journal), he emigrated to Canada in 1951, when he then began his forestry career. He started working at the provincial Department of Lands and Forestry in Geraldton, Ontario after he received his Canadian citizenship papers in 1957. George then spent the next 40 years living in Beardmore working through several different positions within the Ministry. During his time as a forester he established some of the first plantations in Northwestern Ontario, including the Limestone Plantation near Nipigon and Beardmore. He continued to observe and learn from them long after his early retirement from the Ontario Ministry of Natural Resources Nipigon District in 1984. He was well known throughout northwestern Ontario for the contributions he made to boreal forest management. George's main interests were always committed to the growth and long-term development of the boreal forest. George had a European friend who introduced and supported the idea for George to proceed with initiating European partial harvesting systems (CT) in the Canadian boreal forest. Limestone Plantation was established in the early 1960's; the seedlings that were planted came from Fort William and Swastika Nurseries.

Boom Lake site was established in 1960 and Airstrip site was established in 1961. George worked with Aboriginal people and created a special bond with them as they worked for him as tree planters to establish the Limestone plantation. The timeline for the two sites following the planting operations is as follows; In 1966 manual cleaning of poplars and other competition occurred. In 1969 herbicide was used to remove poplars and other competition and in 1971-1980 manual cleaning occurred when required. In 2008 the commercial thinning experiment was established. George would bring his sons out to the sites to do some manual cleaning whenever he felt it was necessary. The herbicide used in 1969 was referred to as Agent Orange. "Agent Orange is a mixture of different herbicides (plant-killing chemicals) and defoliant (a chemical used to remove leaves from plants and trees) (Noakes 2021)". This operation was done with a plane, this caused for a lot less poplar competing in the stand while the black spruce was still young allowing for more positive growth to occur in its favour. George Marek passed away in 2003 at the age of 82 years old and his legacy for committing to the growth and long-term development in the boreal forest has been continued in recent years by CNFER.

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METHODS

2.1 - Study Area and Site Information

This study was carried out in the Limestone Plantation roughly 30 km north of the town Nipigon, Ontario (Figure 1) and 50 km south of the town of Beardmore, Ontario. This study area included two black spruce plantations or sites “Boom Lake” (Figure 2) and “Airstrip” (Figure 3) that are located in the Superior Forest Sections of the Boreal Forest Region of northwestern Ontario. Stand size ranged from 103.1 hectares at the Boom Lake site and 36.6 hectares at the Airstrip site. These stands are situated in ecoregion 3-W (Lake Nipigon Ecoregion). Ecoregion 3-W mainly consists of two forest sections, Nipigon and Superior both of which are located within the boreal forest region. The climate in this region is classed as microthermal and humid, and is characterised by short, warm summers and long, cold winters with approximately 80 frost-free days and a mean annual temperature 0.2 °C (Chapman and Thomas, 1968). Annual precipitation within the Lake Nipigon Ecoregion is fairly high as it ranges from 654 to 879 mm, and precipitation for just the summer rainfall ranges from 231 to 298 mm. On Average, the area receives 760 mm with 60% falling during the growing season (Environment Canada, 2008).

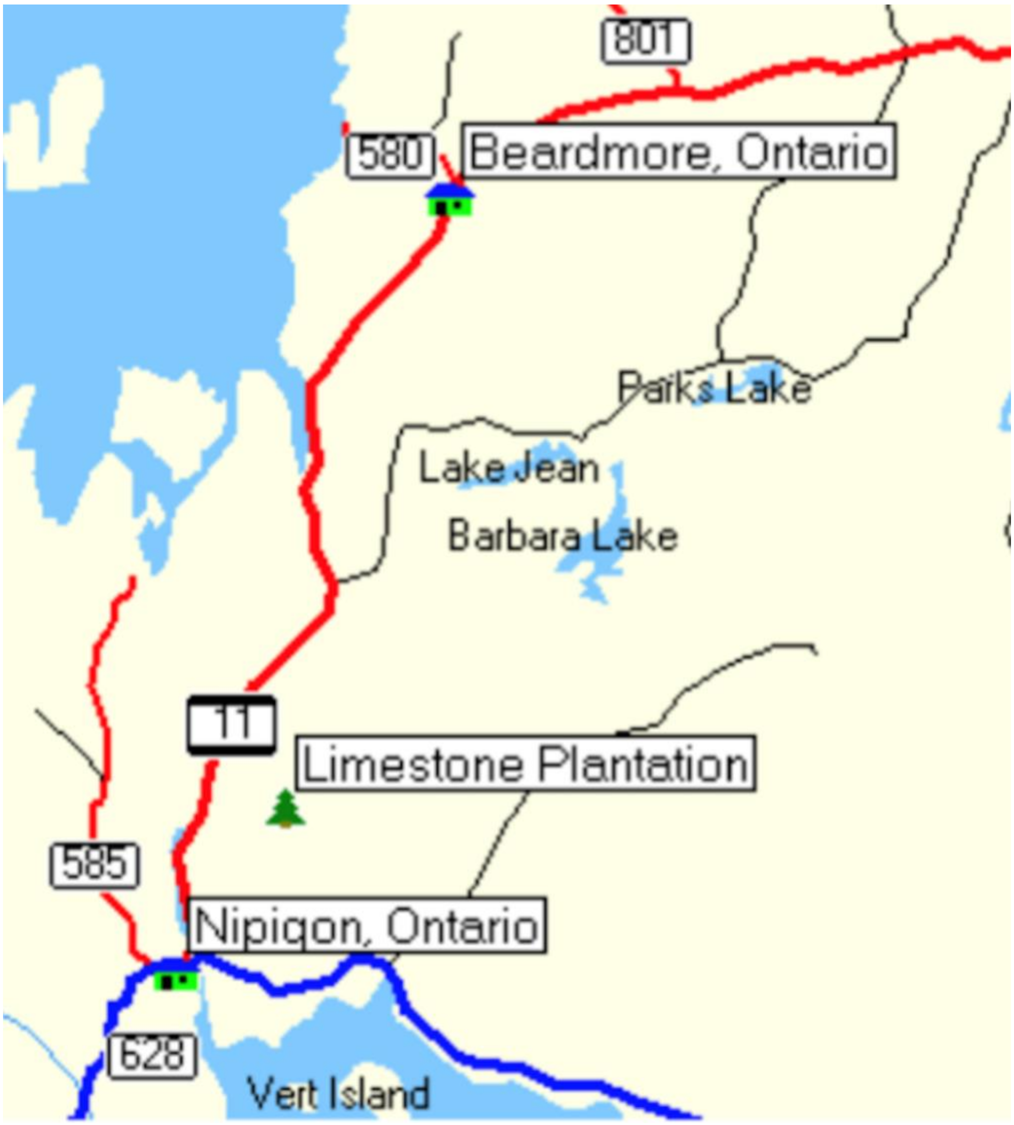

Figure 1: Map of study area relative to the Limestone Plantation in Ontario (Young 2008)

The two sites (Boom Lake and Airstrip) of black spruce selected for this study within the Limestone Plantation were established on a range of landforms and soil types. These sites were chosen for growing black spruce because of high productivity in-regards to overall growth. Commercial thinning operations for both the Boom and Airstrip sites were completed in March and April 2008. The QT and MT were established as operational thinning treatments with more a random extraction pattern while the HT and LT treatments were thinned in defined strips and extraction trails within 1 hectare squared treatment plots.

Between both sites there are multiple differences in the mode of deposition, degree of profile development and textural classes that have caused different site qualities for tree growth expressed by site index. "Based on the site index models developed by (Kwiaton 2008) stands of black spruce, the SI30 values of the study sites were 10.9 m, 13.3 m and 11.8 m for Tyrol, Boom and Airstrip, respectively (Reid et al. 2009)".

The site area where the Boom Lake plantation is situated consists of glaciofluvial deposited medium to fine sand, which is overtopped with a thin, silty loess cap (Young 2008). This site has a well-developed Humo-ferric podzolic profile and is roughly 103.1 hectares in size (Reid et al. 2009). The large area between both plot groupings in the Boom Lake site (Figure 2) is still primarily black spruce; however, it was not included in the study area. This was due to previous researchers in the past driving nails into trees, fertilizing trees, and planting other species in the area. As a consequence of these actions in the past, it was decided to not include those contaminated areas as a part of the thinning experiment (Meek and Reid 2009). The Boom site included five replicates of HT, LT and Control treatments, and three replicates of MT and QT. and three replicates of MT and QT.

Figure 2: Map of Boom Lake Commercial Thinning Site

The Airstrip site is situated on a lacustrine clay plain, with prominent varves throughout the Orthic Gray Luvisolic profile. “These are calcareous clays with carbonates present below 38 cm and parent material pH values above 6.5 (Young 2008)”. The airstrip site included three replicates of the Control, Heavy Thinning and Light Thinning treatments, as well as three replicate permanent growth plots (PGP's) established within an area that was operationally thinned using the quality thinning treatment.

Figure 3: Map of Airstrip Commercial Thinning Site

2.2 - Experimental Design

2.2.1 Random Complete Block Modifications

The design layout used for this experiment at the Limestone Plantation was a Randomized Complete Block Design (RCBD). In forestry research, the RCBD design is one of the most popular experimental designs used. “The design is especially suited for field experiments where the number of treatments is not large and there exists a conspicuous factor based on which homogenous sets of experimental units can be identified (Food and Agriculture Organization of the United Nations 2000)”. This particular experimental design is most effective when the sites are fairly uniform so replicates can be installed. The RCBD generally involves having a space of land divided into squared uniform units to account for any variation so that differences being observed are largely due to true differences between treatments (Grant 2010). Treatments assigned randomly to blocks (RCBD) is a standard design for experiments involved with agriculture and has benefits that include; easy estimation for missing plots; replications between treatments do not require uniformity; and there are no restrictions for the amount of treatments or replicates.

2.2.2 Thinning Treatments

Treatments included four levels of thinning intensity; Light thin (LT) (25% basal area removal of the smallest trees), Moderate thin (MT) (35% basal area removal of the smallest trees (Boom site only), Heavy thin (HT) (up to 50% basal area removal of the smallest trees) and Quality thin (QT) (35% basal area removal of the smallest and/or poorest-quality trees), and Untreated controls. This experiment was established by the Boreal Silviculture Research Program at the Center for North Forest Ecosystem Research (CNFER). In 2006, CNFER went to the Limestone plantation and surveyed the whole stand and identified the areas within the stand that were pure black spruce. Once the pure black spruce areas were identified, they subdivided each stand into 1 hectare treatment plots, then establishing 400m2 growth and yield plots located at the center of each of each of those treatment plots. The heavy equipment used in 2007 for extracting the trees for the commercial thinning treatments was done by a Single Grip Harvester/Forwarder machine called the Ponsee Buffalo, a versatile piece of heavy equipment capable of many tasks. Red Rock Indian Band (Lake Helen Reserve) was responsible for the harvest operations. The contractor was Decicon and their equipment was supplied by Ponsee. Trees were thinned in strips in each 1 Hectare square for both HT and LT. The Ponsee Buffalo extracted the stems for the HT and LT thinning operations along extraction trails (strips) within each 1 hectare treatment plot.

Figure 4: Ponsee Buffalo Harvester Forwarder used for Thinning Operations (Buffalo Advertisement 2022)

All treatments were applied randomly to each 'block', with the exception of QT and MT. QT and MT treatments were established as operational thinning treatments. Operational treatment areas were designed to examine the advantages and disadvantages associated a thinning prescription that strictly focuses on tree diameter (MT; thinning from below) compared to one where larger trees with some sign of defect could be removed leaving smaller trees with better form (QT). The thinning treatments included in this study were carried out by a highly skilled and experienced operator who trained in Finland. In areas where they were strict thinning from below was carried out (LT, MT, and HT) the trees that were to be removed were painted by CNFER technicians. Thinning from below is most commonly used when dealing with a mid-tolerant species like black spruce. QT is more of a "free thinning" operation as it differentiates from MT there was no painted trees for the operator to cut. The operator instead of cutting down just the smaller trees, cut down the less quality trees. Since there was no paint the less quality trees that were cut down were decided by the operator. Trees that were cut within the QT were trees with defects or disease no matter on the size. For the QT treated areas, CNFER did not paint trees for removal. The operator was free to make the cut/no cut decision for themselves. This practice was shown to result with more volume being removed for a lesser cost (Meek and Reid 2009).

2.2.3 Plot Measurements

The measurement data presented in this thesis according to Douglas Reid (pers. comm., February, 2023) were collected using standard Ontario growth and yield permanent growth plots (PGPS). Within each PGP, DBH was measured on every tree and heights were measured on a subset of trees representing the range of diameters present in the plot. Standard Ontario PGPs consist of an 11.28 m radius circular plot. All measured PGPs were located in the approximate centre of each 1 ha treatment area, or at least 50 m from the edge of any other PGP in the operationally thinned areas. CNFER used these plots to measure a representative sample of the tree population. From those diameters, they were able to calculate the basal area of each particular tree. The same trees in the same plots on each site have been measured every five years since treatment plots were established. Only data from the 2017 measurement effort carried out by CNFER were used in this thesis. The specific data components included the following: area identification; PGP identification; tree number; species; diameter at breast height (cm); observed height (m); basal area (m2); total volume (m3) and density. “Density” refers to the stem density. Each plot required has a radius of 11.28 m, this means that there is 400 m^2 within each plot. (11.28 m2*(pi) = 400m2). There was (400m2) per 1 hectare block (10,000m2), so the density was 25 m2 (10,000/400= 25). Total volume of a tree was calculated using Honers volume formula using the observed height and DBH value to derive a total volume value.

2.3 - Analysis

2.3.1 - Tree Height Estimates

The heights of trees were measured on a subset of trees in each plot, and all tree diameters were measured. For the trees that were not measured we predicted heights using non-linear models of the Chapman-Richards variety (Ht_tot ~ 1.3 + a * DBH_10^b) to predict height for the various species present in the plots (Sb, Sw, Pt). The values “a” and “b” within the formula are the parameters which were used determine the shape of the curve for the estimation of heights from DBH values. For each species, parameters were derived for each site by researchers at CNFER from the subset of trees for which height and diameter were both measured in 2017. New models were derived to make more accurate predictions for tree measurements as they are now taller than when the previous measurements occurred with the older model. This gave us our best bet as to how the growth of height could be predicted.

Inherent differences between the two sites were accounted for in the estimation of heights from diameters by deriving separate models for each species on each site. The Boom site had a total of 21 PGP’s which consisted three other species than black spruce. Within the

Boom site there was 32 white spruce (*Picea glauca*), 1 white birch (*Betula papyrifera*), and 72 trembling aspen (*Populus tremuloides*) throughout the sites 21 PGP's. One of the PGP's at the Boom site was purely white spruce and contained 21 of the 32 white spruce. The pure white spruce PGP were in a LT treatment block. For the Airstrip site there was a total of 12 PGP's which also consisted of the same three other species not including black spruce. Within the Airstrip site there was 1 white spruce, 1 white birch and 48 trembling aspen throughout the sites 12 PGP's. As you can see the Boom site has much higher numbers of other species present within its blocked compared to the Airstrip site, especially white spruce and trembling aspen. Each site used different parameters of the same species for their models to account for differences in the relationship between diameter and height at the two sites. A black spruce model, all spruces model (Sx), trembling aspen model and a deciduous model were each specifically designed for each site. The all spruces models were used on white spruce trees and the deciduous models were used on white birch trees. For the Airstrip site the black spruce model was applied to 618 black spruce trees; all spruces model was applied to 1 white spruce; trembling aspen model was applied to 48 trembling aspen; and deciduous model was applied to 1 white birch. The Airstrip site had 565 out of the 618 (91.4%) black spruce estimated using models. For the Boom site the black spruce model was applied to 850 black spruce trees; all spruces model was applied to 32 white spruce; trembling aspen model was applied to 72 trembling aspen; and deciduous model was applied to 1 white birch. The Boom site had 732 out of the 850 (86.1%) black spruce estimated using the models.

2.3.2 Statistical Analysis

In order to test to the Null hypothesis, we had to determine if there was a difference present on the effects between the four different commercial thinning treatments and the two control sites. Blocks were stratified into five groups (four thinning treatments and control treatment). The data used for this thesis is based on the measurements made Year 10 post treatment. Basal area was calculated from the area of a circle (radius equal to DBH/2) and stem volume was calculated using Honer's volume equation for black spruce. Analysis involved the use of an ANOVA (analysis of variance). This is how we tested for differences in response variable means associated with site, treatment and site by treatment interaction.

The effects of site and treatment were evaluated for a number of response variables that are of importance to forest mangers; DBH, tree height, basal area, and total volume using an ANOVA test. An ANOVA test simply shows you whether any of the mean values differ from one another based on the factors accounted for in the model, in this case site and treatment. The means being analyzed in this experiment was for each of the response variables (DBH, height, volume and basal area). All plots could not be included in the initial ANOVA due to not having MT treatments at Airstrip. To see if there were differences present between MT and QT treatments at the Boom site a Welch Two Sample T-test was conducted for measured DBH and height. The results of the T-test results showed that there was no statistically significant difference in mean DBH or height between the MT and QT treatments on this site. Since the diameters ($p = 0.7232$) and heights ($p = 0.6731$) were insignificant and did not differ we combined the QT and MT treatments at Boom site for the purpose of our analysis.

The results derived from the ANOVA would indicate whether effects had any statistically significant differences between groups or not. For each plot, mean DBH and basal area were determined from all trees measured in each plot. Mean height and mean volume associated with each plot included trees where height had been estimated using the CR model described in Section 2.3.1. Where the analysis of variance indicated significant effects, the Tukey test was used post hoc to conduct pairwise comparisons of means between groups.

RESULTS

When analyzing the results, researchers are looking for the significant effects from site location and different thinning treatments in respect to the response variables of DBH, BA, Height and Volume. Significant effect results are derived from a two factor ANOVA test. Results are determined significant when the means involved in that two factor ANOVA test differ from each other. When differences are present among means a post hoc Tukey test is then implemented when comparing more than two means and gives more precise information as to what treatments specifically differ from each other. From this information we can answer our research question and state whether or not a response variable had a direct effect from CT operations or not. Results are put in logical order based on what was obtained first. DBH results were derived tree measurement (measured and predicted). BA results were derived based on the DBH values. Height results were estimated from the DBH values. Volume results were estimated from both DBH and height values.

Commercial thinning had significant effects on DBH, as there were differences present in DBH across both sites ($p = 0.01463$; Figure 5) and treatments ($p = 0.04648$; Figure 6).

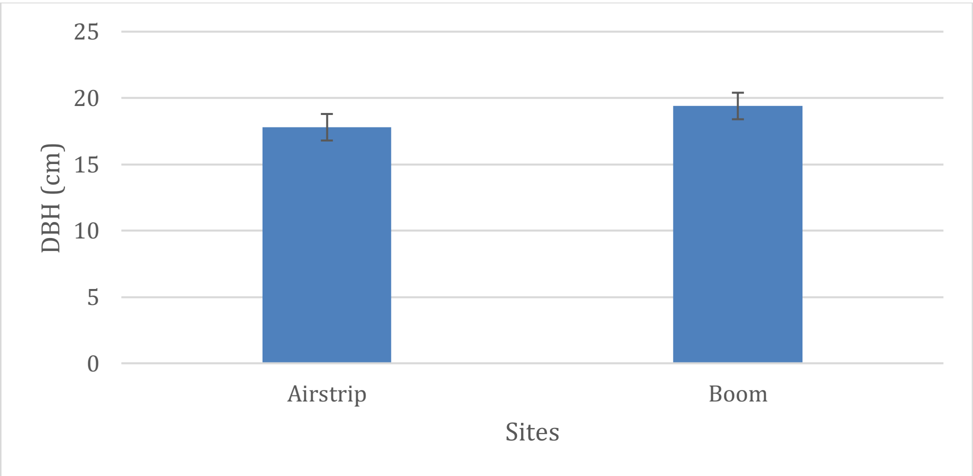

Figure 5: Average DBH between Sites

Post hoc analysis determined that mean DBH differed between C and HT treatments ($p<0.05$), but that no other pairwise comparisons were statistically significant (Figure 6).

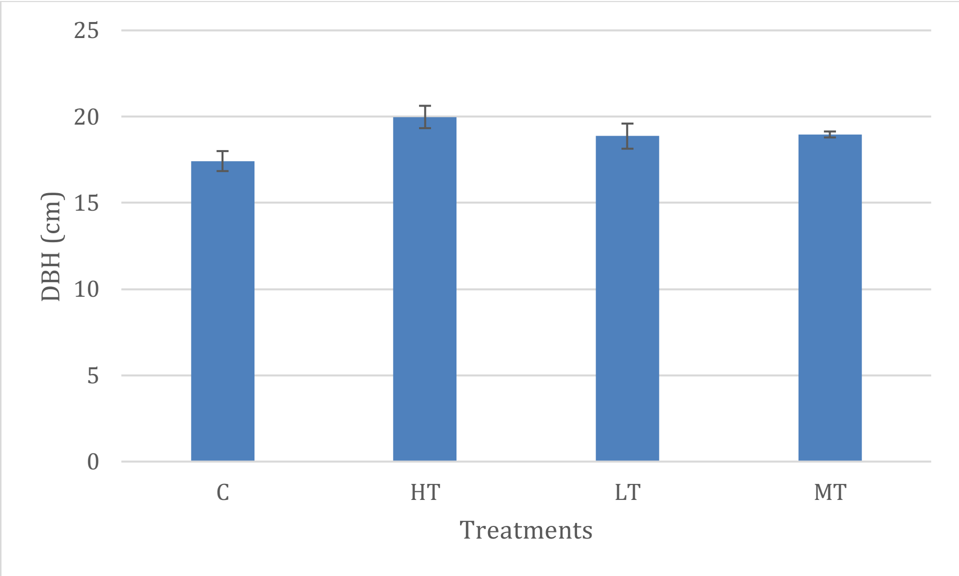

Figure 6: Average DBH between Treatments

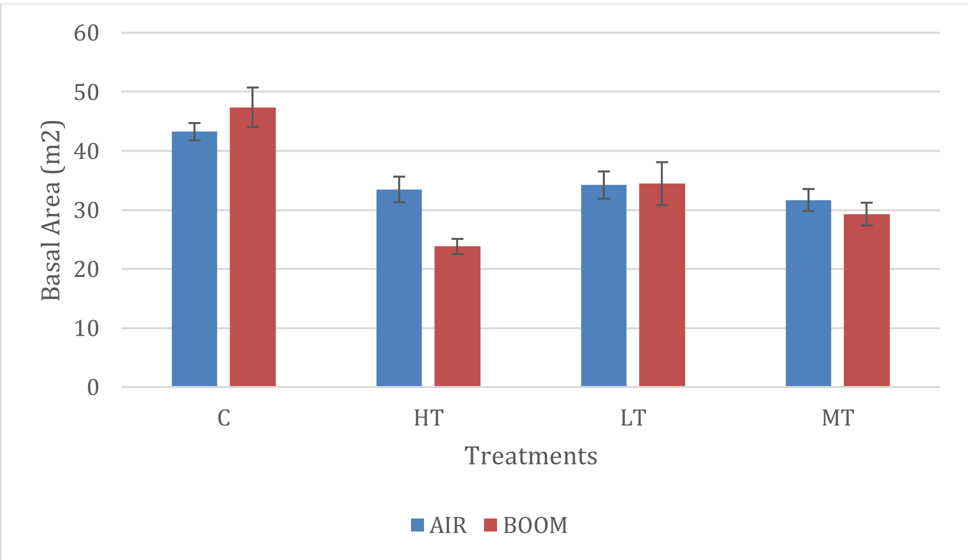

Figure 7 : Average Total Basal Area between treatments and sites

There is a moderately significant effect of commercial thinning on Treatments ($p = 0.05029$) and a moderate interaction effect of thinning between Site and Treatment ($p =$

0.09615) for Basal Area. Post hoc Tukey test was used between means to distinguish exactly where the differences occurred between means for treatment effect. Based on Tukey test for Total Basal area the differences found were between the controls and the treatments. No statistically significant differences were found between the thinning treatments in terms of BA 10 years after treatment. .

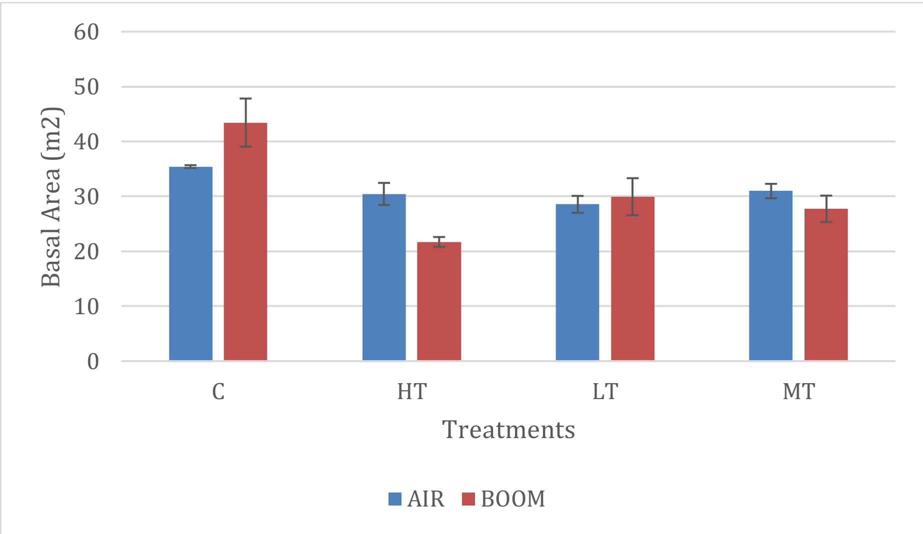

Figure 8: Average Spruce (Sx) Basal Area between treatments and sites

There was a significant difference in site by treatment interaction for Spruce (Sx) Basal Area ($p=0.04455$; Figure 8). The direction of differences between TMT is different depending on SITE. A violation was discovered in the assumption of residuals being normally distributed. The assumption of normal distribution in residuals for both the analysis of Total BA and Spruce BA was violated ($p=0.006$) due to one control plot having a much higher BA than would be expected from the model. Post Hoc Tukey test (Table 3) was implemented for evaluation of differences associated with the SITE by TMT interaction. Where $p<0.05$ can say there is a significant difference between means.

There were no significant effects on total height of all tree species present, including treatment (p = 0.3430), site (p=0.1993) and the interaction between treatment and site (p=0.9594). For black spruce heights, however, there were significant effects associated with the interaction between site and treatment (p=0.010990; Figure 9) as well as the main effect of treatment (TMT) (p=0.001917; Figure 9). These results include using all estimated heights from our PGPs based on DBH, but the one plot containing all Sw trees (LT at Boom) was not included.

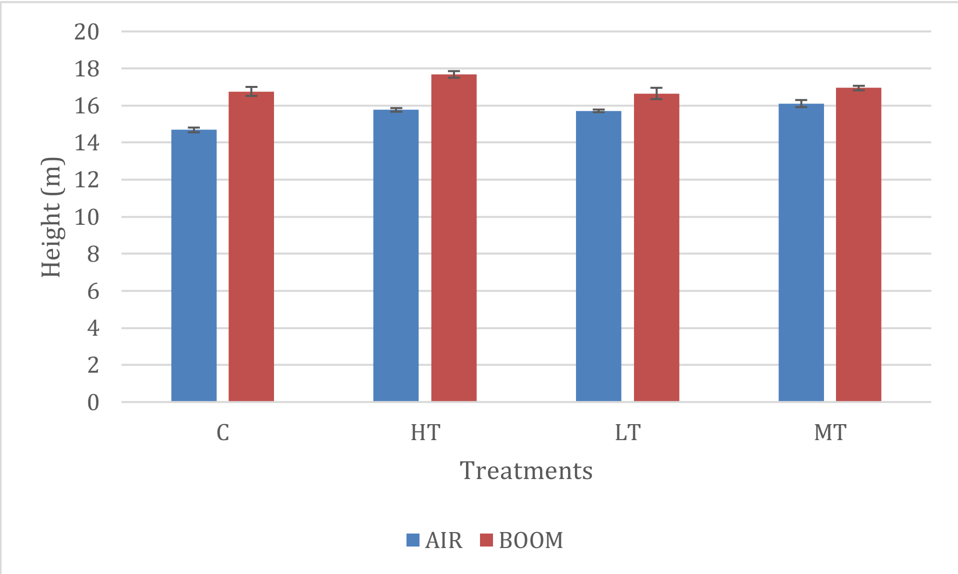

Figure 9: Average Black Spruce (Sb) Heights between treatments and sites

The post hoc Tukey test showed that the difference between C and HT is significant (HT DBH is higher than the Control), but that there is not a statistically significant difference between any of the other groups.

There were no significant effects of treatment (p=0.15830) and site (p=0.07920) or of the interaction between treatment and site (p = 0.08887) for total volume. However, for spruce volume (Sx) there were significant differences found between the sites in terms of mean volume (p = 0.01338; Figure 10). More importantly there was also a difference discovered between treatments but only for some sites (p = 0.03574; Figure 10). Once again used a Post hoc Tukey test for evaluating the comparisons between means to distinguish exactly where the differences occurred. There was also a difference discovered for Sx volumes between treatments, but only for the Boom site.

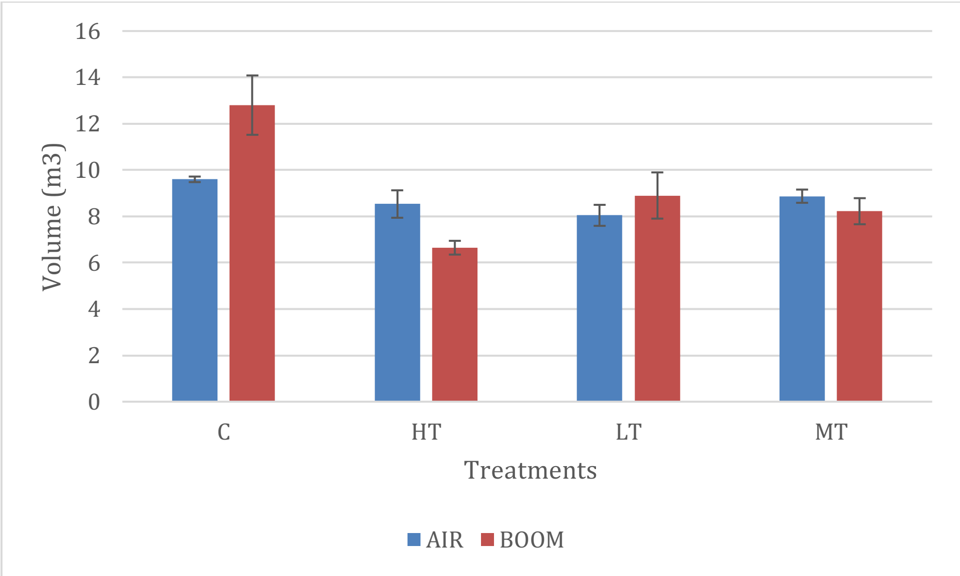

Figure 10: Average Spruce (Sx) Volume between treatments and sites

DISCUSSION

4.1 - DBH

After analyzing the response variables of DBH, it was determined that Commercial Thinning had significantly different effects on the Site location and Treatment type. Commercial thinning had a significant effect on DBH, as there were differences present in DBH across both sites (P = 0.01463; Figure 5) and treatments (P = 0.04648; Figure 6). The mean difference in DBH between sites was 1.6 cm as the mean for the Boom Site was 19.4 cm and the Airstrip Site was 17.8 cm. This can be due to the Boom site having higher site index with quality soils (silty loam) compared to the lesser quality soils found in Airstrip site (clay). Mean DBH differed between C and HT treatments, with Heavy Thinning having a mean value 12.7 % greater than the Control mean. There were no statistically significant differences between any of the other treatment groups in-regards to DBH. The fact that smaller stems had been removed from the thinning treatments but not the controls is likely why this difference persists after 10 years of growth following the application of treatments. The HT treatment would have had the most smaller diameter stems removed.

Results for the diameter growth at the Limestone Plantation were similar to the New Brunswick study (Pelletier, 2008) as they too discovered that all of the thinning treatments satisfied the objectives of focusing diameter growth on a reduced number of stems. However, the Limestone study, examined in this thesis, did not show all treatments increasing in diameter growth, and only had significant differences among HT and Control treatments. The study done in Kapuskasing, Ontario, had similar results as they also stated that only heavy CT had a significant and positive effect on annual radial growth in plantation-grown black spruce. This close relationship between the Limestone Plantation and

Kapuskasing studies can be due to the similar forest and sites, as they both are situated within the boreal forest whereas the New Brunswick study was carried out in the Acadian forest. The average DBH of trees within HT within the Limestone Plantation was 20.0 cm, whereas the Control treatment average DBH was 17.4 cm. This difference can be due to the fact that HT, LT and MT had their smallest stems removed in 2007 during the CT operation and Control treatments were left the same. LT treatment had an average DBH of 18.9 cm, and MT had an average DBH of 19.0 cm. However, the post hoc test indicated that the differences in mean DBH between HT, LT and MT were not statistically significant.

4.2 - BASAL AREA

For total basal area (BA; m^2 ha^{-1}) there were moderately significantly effects of site and for the interaction between site and treatment suggesting a possible trend (Figure 7). Based though treatment ($P=0.05029$) and the interaction between site and treatment ($P=0.09615$) were not statistically significant, a post hoc Tukey Test was conducted to examine the treatment effect more closely. Based on the Tukey test for Total BA, the differences found were between the controls and the treatments; all thinned treatments had lower basal area ($p<0.05$; Figure 7). For the interaction, it appears that the means between thinned treatments (HT, MT, LT) differed on the Boom site, but not on the Airstrip site, though all appear lower than the Controls.

For spruce (Sx) Basal Area (BA), there was a significant site by treatment interaction effect ($P=0.04455$; Figure 8) and a weak site effect ($P=0.05815$). This indicates that differences in mean Sx BA between treatments differ between sites. These results should be interpreted with caution because the assumption that model residuals are normally distributed was violated (Levene's Test for Homogeneity of Variance; $p=0.006$). This violation was due to one control plot having a much higher BA than would be expected from the model. Average Sx BA at the Boom site was 30.7 m^2 compared to 31.3 m^2 at the Airstrip site, though this difference was not statistically significant. The Control treatment at the Boom site has the highest mean Sx Basal Area (43.4 m^2 ha^{-1}) compared to all other treatments. The next highest mean Sx BA was in the control treatments at Airstrip (35.4 m^2 ha^{-1}). Boom control treatment is averaging 22.5 % more Sx basal area than the second highest treatment mean. The BA results for Total BA and Sx BA were comparable to results from (Hasenauer et al. 1997) who determined that there is no evidence that basal area of thinned plots will exceed plots that are un-thinned (controlled). Within their study they realized that competing hardwoods within the stands had a significant impact on the results.

4.3 - HEIGHT

Though there were no significant effects from the sites or the treatments on mean heights from all species combined. However, when analyzing just the means of measured and estimated black spruce heights, there was a significant a significant area by treatment interaction effect (P=0.010990), as well as significant treatment (P=0.001917) and site (P=3.743e-07) effects. The black spruce heights at both sites were assessed at the stand or plot scale and the height values derived show us that there are differences present between sites in terms of site quality. As mentioned in Section 2.1, Boom site has a slightly higher quality index than the Airstrip site, this can be due to subtle differences in nutrients or water availability between treated plots. The mean for pure black spruce height at Boom was 17.01 m and Airstrip was 15.56 m. Total height most likely had the smallest means due to involving smaller hardwoods within their measurement data. Sx had larger means than Pure black spruce due to the white spruce within the Sx data being generally larger than the black spruce. A reason as to why Boom may have such a higher value in-regards to Sx height compared to Sb height can be due to the fact that within the Boom site there was a PGP_ID that was Pure white spruce, which were generally bigger and therefore made the Sx height means larger than Sb height means.

Since our mean black spruce heights had significant interaction and main effects we conducted a post hoc test on black spruce height at the plot level. Though mean black spruce heights at Airstrip were generally lower than those observed at Boom, the only within site difference at Airstrip was between the Control and the MT treatments ($p = 0.0059$). At the Boom site pairwise comparisons indicated that mean height values were higher in HT and LT treated areas in comparison to the Controls (HT = 17.68 m) (LT = 16.65 m) (C= 16.76 m). (Pelletier 2008) found that total stand height was not affected by any thinning in general. The total stand height data was specifically looking at Sx (Sb or Sw) only and only measured trees from the 2017 data. Differences in height associated with these interactions may reflect inherent differences in site quality between treatments. From the perspective of assessing the effects of commercial thinning treatments on stand growth, it may be more meaningful to examine height increment as multiple years of measurements are available in the CNFER data set.

4.4 - VOLUME

Though no significant effects of the site or treatment were observed for total volume, there was a significant site by treatment interaction effect and an effect of site on mean plot-level spruce (Sx) volume (Figure 10). Mean Sx volume for Boom site was 9.14 m3 per plot and was 8.76 m3 per plot at the Airstrip Site. There was also a difference discovered for Sx volumes between treatments, but only for the Boom site. The results of this study were comparable to the results of other similar studies (Tong et al. 2011, Bose et al. 2018), that black spruce does increase volume growth with CT and will differ among treatments as more area is removed. For Spruce volume, the site by treatment interaction tells us that Sx volume differs between treatments but only at the Boom site (Figure 10).

Immediately after the thinning treatment was conducted in 2007 (year 0), volume was lower in all thinned areas. Ten years after the commercial thinning treatment was conducted, Sx volume still differed between the C and the HT, LT and MT at Boom. Control sites still remain higher since there are more trees. At the Airstrip, there is still no difference between the control sites and the sites with thinning treatments. Bose et al. (2018) showed that on average, tree volume growth was 31% higher in thinned stands relative to un thinned stands irrespective of species and tree size. These results were comparable to the Kapuskasing Study done by (Tong et al. 2011) who mentioned within their results that heavier thinning is more effective on annual growth because increased carbohydrate production trees because of less competition and increased amount growing space.

CONCLUSION

There were significant effects of site and treatment on DBH, that reflect differences between the two sites and the fact that smaller diameter stems were removed from all thinning treatments. Differences in moisture and nutrient availability (site quality) are the most likely explanation for the site by treatment interaction effect associated with black spruce heights. The significant site by treatment interaction effect for spruce BA and Volume suggest that individual tree growth in the thinned areas has allowed for these stands to recover from the thinning operation quite quickly (10 years) at the Airstrip site, but not at the Boom site. At the beginning of the experiment in 2007 trees were on average larger in the Boom site compared to the Airstrip site, reflecting higher site quality at Boom. Treatment effects observed on both sites largely reflect differences between controls and the various thinning treatment (MT, HT and LT). Control values (means) are generally higher than treatment means since the controls had no BA removal.

The commercial thinning treatments do show promise for forest managers to realize mid rotation merchantable volume, however, more study is needed to understand the long-term effects and growth responses of residual trees left after thinning. These sites are a unique research opportunity deserving of future study as they age, to further understand the effects of commercial thinning in black spruce plantations on boreal forest sites.

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