Long-Term Impacts of Commercial Thinning and Nitrogen Fertilization on Lodgepole Pine: A Two-Decade Analysis of Growth and Temporal Dynamics

by

Apsana Kafle

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

Master of Science
in
Forest Biology and Management

Department of Renewable Resources
University of Alberta

Abstract

Commercial thinning and fertilization are potential silvicultural tools to enhance Alberta's Forest productivity in an imminent timber supply gap. In 2000, an experiment was initiated in a 68-year-old lodgepole pine stand located in Alberta's upper foothills, using a 2x6 factorial design. Commercial thinning, removing 50% basal area was carried out at two levels (thinned and unthinned), while nitrogen fertilization was applied at six levels (No fertilizer, 200 kg/ha N Urea + Boron, 200 kg/ha N + blend, 400 kg/ha N + Boron, 400 kg/ha N + blend, and 400 kg/ha N Ammonium nitrate + Boron). Two studies were conducted, utilizing 20 years of post-thinning data, to analyze: a) the individual and combined effects of thinning and fertilization on growth and mortality and b) the temporal growth response to commercial thinning using tree cores. Key findings of the first study were that commercial thinning led to an increase in the cumulative merchantable volume (the volume removed at the time of thinning + the final standing volume) and the proportion of trees suitable for good sawlogs (>20 cm DBH) by 20%. Individual tree DBH was enhanced through thinning and fertilization treatments, both individually and in combination. This indicates that trees subject to both thinning and high fertilization (at 400 kg/ha levels) exhibited the greatest individual growth. From the second study we found the size of individual trees at the time of thinning significantly predicted their subsequent growth for both studies. Smaller trees (10.1-12.5 cm) exhibited a delayed response to thinning within the first 5 years, followed by a slow growth increment. Medium-sized trees (12.5-17.5 cm) displayed an immediate growth response to thinning but declined after 15 years. The largest trees (17.6-20 cm) exhibited a slower growth response, which persisted beyond 15 years. Consequently, commercial thinning and fertilization can serve as a viable management tool to enhance the growth of natural lodgepole pine stands in Alberta.

Keywords: fertilization, growth, size, timber

Preface

This thesis incorporates data obtained from West Fraser- Hinton Wood Products and data collected by Apsana Kafle during the summer of 2022. The author of the thesis took responsibility for the research design, data organization, partial data collection, data analysis, and manuscript writing. Dr. Bradley D. Pinno contributed to the research design, aided with data analysis, and edited the manuscript. Dr. Robert E. Froese provided support with data analysis and manuscript edits as well.

The partial findings of this thesis, titled "Commercial Thinning and Nitrogen Fertilization on Lodgepole Pine: A 20-Year Study on Growth," were shared through a presentation at the Growth and Yield Innovation Conference 2023 in Canmore, Alberta. Additionally, the results were presented as a poster at the 88th and 89th Forest Industry Lecture Series held at the University of Alberta. It is important to note that none of the content from this thesis has been published before.

Acknowledgments

I wish to take a moment to extend my sincere gratitude to the individuals who have played a pivotal role in the successful completion of this thesis. Their unwavering support, invaluable guidance, and steadfast encouragement have been instrumental in making this academic journey possible.

First and foremost, I would like to express my deepest appreciation to my advisor and mentor, Dr. Brad Pinno. Brad, your belief in me, coupled with the opportunity you provided to pursue my passion far from home, has been transformative. Your consistent guidance, insightful feedback, and unwavering encouragement have not only shaped the trajectory of this research but have also influenced my overall approach to learning and growth.

I am immensely grateful to Dr. Robert Froese for graciously accepting the role of committee member and for his continuous support and guidance throughout this process. His constructive feedback has significantly contributed to refining the direction and quality of this work. A special mention of gratitude goes to Dr. Jen Beverly for her willingness to serve as my external examiner; your time and dedication are truly appreciated.

My heartfelt thanks extend to Ms. Sharon Meredith and West Fraser, Hinton Wood Products, for their invaluable support in providing necessary resources for my research. I would also like to express my gratitude to Dr. Brian Roth for his unwavering support and the opportunities he has afforded me to present this work at various forums.

In times of confusion, the guidance of Dr. Sesh K. Bhandari and Dr. Mostarin Ara has been invaluable, and I am deeply appreciative of their assistance. A special acknowledgment goes to Sakar Jha for his contribution to the data analysis of both projects. I am profoundly thankful for the camaraderie and unwavering support of my friends from the Silviculture lab –

Laura Manchola-Rojas, Keana Trudel, Francis Scaria, Surabhi Lukose, Stephania Hinse, Ethan Ramsfield, Benjamin Strelkov, and Andrew Sperling. Your presence has been a constant source of encouragement.

To the wonderful friends I have had the pleasure of making at U of A – Rishap Lamichhane, Abhijeet Pathy, Sarun Khadka, and Mohammed Mubasher – your companionship and support have been cherished. My heartfelt gratitude goes out to my family for their unwavering belief in my abilities. Your encouragement has been my driving force and my cornerstone.

Finally, to every individual who has contributed, regardless of the scale, to this endeavor, your efforts have indelibly impacted both my academic and personal growth. From the depths of my heart, thank you for your contributions.

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CHAPTER I: LITERATURE REVIEW

1.1. An insight into timber supply and forest management in Alberta

Canada has 362 million hectares (ha) of forests, which account 9% of the global forest area and 40% of the country's land base, making it the third-largest country in the world by forest coverage (Natural Resources Canada, 2021). The forestry sector is a significant economic driver, generating employment for 1.1% of the country’s workforce and revenue through timber export worth of $45 billion in 2021 (Natural Resources Canada, 2021). The principal source of timber is from the public land which covers 90% of the country’s forests area. Harvesting of timber is guided by the principle of “sustainable wood supply” which refers to the volume of timber that can be harvested annually from federal, territorial, and provincial land while meeting the environmental, social, and economic opportunities. Although sustainable timber supply is the maximum wood that can be harvested, harvests from provincial crown lands are regulated by the Annual Allowable Cut (AAC).

The effects of forest-based disturbances like fire, insect infestation and drought have significantly impacted the ecological processes of forests and poses a threat to sustainable timber supply (Brecka et al., 2018; Rowan, 2012). For instance, in 2020 the total timber harvest from across Canada was 139.8 million m^3, which was below the estimated sustainable wood supply level of 218.1 million m^3 due to a substantial decrease in timber volume by natural disturbances including wildfire and pest infestation mainly in British Columbia (Natural Resources Canada, 2021). This decreasing timber supply is expected to bring short- and long-term impacts to the forest-based industries, leading to decreased flexibility and a narrower time span for managing their capital stocks. This situation can result in reduced job opportunities, increased harvest to meet and further decline in the long-term timber availability (Brecka et al., 2018).

In Alberta, provincial land is the source for 90% of the timber supply, regulated through the Annual Allowable Cut (AAC) of 29.6 million m^3 (17.2 million m^3 for conifers and 12.4 million m^3 for deciduous trees) (Alberta's Forest Economy, 2021). The AAC for conifers in some parts have been increasing over time due to forest management practices that increase growth rate of post-harvest stands (Lieffers et al., 2020). However, there is a long-term decline in forestry land bases due to increasing evidence of forest-based disturbances wildfires, pests, droughts with conversion of forest lands for industrial development and protected areas (Pinno, 2021). Despite this, the Government of Alberta intends to increase timber harvesting and the AAC on public lands by up to 13% to promote the viability of the forest-based industry (Government of Alberta, 2020). Due to this contradictory notion, studies have forecasted a short- to mid-term timber supply gap in Alberta.

A decrease in timber supply can have a significant impact on the economy, given that forestry is an important economic sector that contributed \$13.6 billion in economic output, \$5.8 billion in the provincial GDP and supported more than 31,500 jobs in 2019-2020 in Alberta (Alberta's Forest Economy, 2021). Consequently, urgent interventions in forest management are required to avert a reduction in timber supply and to elevate sustainable timber harvest levels in the province. These objectives can be achieved by enhancing the growth of the remaining forests, mitigating the risks posed by disturbances and growing genetically improved seeding with more adaptable characteristics (Pinno et al., 2021b).

Studies suggest that intensive silviculture treatments can be implemented within specific zones in Alberta to achieve objectives such as: a) ensuring a resilient timber supply in response to disturbance and climate-related risks, b) maintaining the flow of second growth timber with appropriate dimensions, and c) ensuring the long-term sustainability of the forest industries, a crucial sector for employment within the province (Hossain et al., 2022; Lieffers et al., 2020). Intensive silviculture is a forest management approach aimed at of augmenting both the volume and value of future forest within a sustainable management context. This approach may include activities across different rotation stages, including site preparation, prescribed fire, application of herbicides and fertilizers as well as density management treatments like pre-commercial and commercial thinning. (Rubilar et al., 2018). Insights from Nordic regions, such as Denmark, suggest intensive management practices has doubled the annual growth of natural pine to 4.3 m^3/ha in the last 50 years (Senko et al., 2018).

Despite the potential to increase stand Mean Annual Increment (MAI) from 2-4 m^3/ha/year to over 8 m^3/ha/year and feasibility to implement due to high productivity forests and well established road bases, intensive silviculture is not yet commonly practiced in Alberta (Pinno et al., 2021a). Several factors constrain implementation in the public lands of Alberta including insecurity of land tenure for private firm owners in public lands, forest regeneration standards that are not sufficient for future commercial thinning (e.g., current restoration density standard is 1200-1400 stems/ha but at least a density of 1800-2000 stems/ha is needed for commercial thinning), and the perception among policy makers that intensive management is uneconomical (Hossain et al., 2022; Lieffers et al., 2020).

Furthermore, intensive silviculture can contribute to reducing pest and drought severity by enhancing residual tree vigor and water use efficiency, as well as mitigating fuel loads susceptible to fires (Donner and Running, 1986; Sohn et al., 2016). Stands subjected to intensive treatments are also more readily available for salvage operations, meaning that even if they are affected by disturbances, the overall value of the stand is not entirely lost (Pinno et al., 2021a). To meet the forest sustainability goals in Alberta, intensive silviculture practice needs to be normalized in forest management planning. This can be achieved through increasing recognition of intensive silviculture beyond traditional practice, incorporating intensive silviculture in current growth and yield models, integrating into economic forms such as Annual Allowable Cut (AAC) and increasing the skills of planning and operational foresters (Pinno et al., 2021a).

1.2. Commercial thinning and fertilization in lodgepole pine

Lodgepole pine (*Pinus contorta* Dougl. ex Loud. var latifolia Engelm.) also known as Alberta's provincial tree, is one of the primary conifer species in Alberta and western North America (Alberta's Forest Economy, 2021). The species covers over 5 million hectares in the United States and 20 million hectares in Canada (Government of Alberta, 2012). In Alberta it make up more than 41% (over 600 million cubic meters) of the provincial coniferous growth stock (26% of the total growing stock in the province) (Alberta's Forest Economy, 2021). This species has been able to maintain its dominance in Alberta through its ability to regenerate naturally and due to silviculture measures conducted after harvesting (Dempster and Meredith, 2014). Under natural conditions, lodgepole pine regenerates abundantly following wildfire with a maximum stocking rate of 100,000 stems/ha (Mitchell et al., 1983). In these dense stands, crown competition affects the space available for growth and light, similarly root competition reduces the availability of water and nutrients to individual trees, ultimately slowing down growth and also leading to mortality (Keane and Weetman, 1987; Prescott et al., 2019). Intensive silviculture treatments such as initial spacing, pre-commercial thinning, commercial thinning and fertilization have been used in natural and planted lodgepole pine stands to promote individual and stand level growth (Blevins et al., 2005; Cochran and Dahms, 1998; Das Gupta et al., 2020; Sullivan and Sullivan, 2016).

Commercial thinning involves removing trees before the final harvest for reducing competition and distribution of growing space (Boivin-Dompierre et al., 2017). Globally, commercial thinning is practiced for improving the condition of the forest stand, improving the wood quality, decreasing the rotation length and to achieve early returns from the forests (Girona et al., 2017; Peltola et al., 2007). In terms of timber supply, commercial thinning offers advantages such as early returns of fiber compared to the full rotation length, capturing volume that would otherwise be lost due to mortality (Pelletier and Pitt, 2008), increasing the piece size and stand value. Additionally, commercial thinning has the potential to reduce forest susceptibility to disturbances such as wildfire (Agee and Skinner, 2005), mountain pine beetle infestation (Mitchell et al., 1983). It can also help diversify the age structure of forest, creating opportunity for timber supply in regions with uneven age classes (Sullivan and Sullivan, 2017).

Commercial thinning has been shown to boost individual and stand level growth up to 31% in North American conifers and maintain productivity throughout the life cycle of the forest (Bose et al., 2018). Despite having potential to enhance growth and yield of forest stands in Western Canada, commercial thinning isn't a widely practiced method of silviculture (Griess et al., 2019), and in Alberta uncertain response on the major species constrain the wide application (Pinno et al., 2021a). To date, there have been limited commercial thinning studies conducted focusing on lodgepole pine. These available studies have generally observed an increase in growth response at both stand and individual tree levels following commercial thinning (Ara et al., 2023; Das Gupta et al.,2020; Navratil et al., 2002). However, the findings of these studies are yet not sufficient to form operational thinning response as lodgepole pine shows variable responses depending on individual and stand characteristics such as age, site index, size at thinning etc (Kishchuk et al., 2002; Prescott et al., 2019; Sullivan et al., 2020).

Thinning increases the growth efficiency of residual trees, meaning that trees of the same size grow more on the thinned than unthinned stands. For example, diameter increment of lodgepole trees in thinned stand was doubled unthinned trees in 15 years (Das Gupta et al., 2020). The individual tree response also varies by their size, this phenomena is known as growth dominance (Chen et al., 2022), and is positive when the growth of larger trees is higher than smaller trees, and negative when small trees have a greater growth (Zhao et al., 2022). Positive growth dominance occurs when thinning creates asymmetric competition for resources use and has been generally reported in shade intolerant species (Thomas, 1997). A study conducted on 50-years-old lodgepole pine, has reported that co-dominant trees with diameter ranging from (10.1-15 cm) exhibited twice the diameter increment compared to the unthinned stands over a 15-year period. This growth enhancement was attributed to release from competition from larger trees for light resources (Das Gupta et al., 2020). However, only one study has confirmed the phenomena, and the relationship between tree size and post thinning growth response is not widely known in lodgepole pine. Therefore, gaining a better understanding of how individual trees across the size distribution respond to post-thinning conditions is necessary to develop management prescriptions in Alberta.

Growth projection studies conducted in Alberta have indicated that implementing commercial thinning practices can lead to a potential increase of 50 m^3/ha in large saw log volume (diameter > 20 cm) by the age of 50 (Hossain et al., 2022). This augmented volume of high-quality logs has the potential to generate a higher volume of sawn lumber per cubic meter, consequently enhancing the overall net value of the forest stand (Soucy et al., 2012). However, significant logging areas in Alberta such as Hinton and Edson, predominantly consist of lodgepole pine forests with stands older than 70 years (Jones, 2014). Only two studies have been conducted thus far on these older stands (Das Gupta et al., 2020; Navratil et al., 2002), and their findings alone are insufficient to derive comprehensive management implications. This is because lodgepole pine response to thinning practices can vary depending on site quality and thinning intensity (Johnstone, 2002; Navratil et al., 2002). Therefore, conducting more in-depth studies on these natural and older rotation stands in Alberta is necessary to gain a more comprehensive understanding of their management requirements.

Nutrient availability is another major factor limiting the growth and productivity of lodgepole pine stands in western Canada. In a natural fire-originated lodgepole stand, this limitation could occur due to volatilization of nutrients like nitrogen, sulphur and boron during the fire events, which have low volatilization temperatures (Brockley, 2000). The demand for soil nutrient also increases with size and age of trees, and during this stage the soil nutrient availability has also declined affecting the growth of lodgepole pine trees (Blevins et al., 2005; Yang, 1985).Therefore, forest fertilization can be adopted as a cost-effective strategy to enhance forest productivity by providing additional nutrients to the soil (Fox et al., 2007).

Based on empirical research, it has been observed that the growth response of lodgepole pine to fertilization exhibits a wide range of outcomes, demonstrating significant variability(Reid et al., 2017). The extent of this variability is influenced by various factors, including the frequency of fertilizer application, site index, season of application, nutrient combination, quantity of fertilizer and many more (Brockley, 2001; Pinno et al., 2012; Sullivan et al., 2020; Sullivan and Sullivan, 2017). Past studies reveal repeated application of nitrogen fertilization have been more beneficial in promoting stand and tree productivity than conventional (single) application, as single fertilization effect typically lasted for four to five years (Brockley, 1990; Kishchuk et al., 2002; Weetman, 1988). Response of lodgepole pine to fertilization can also vary based on site index; studies have shown lodgepole pine stands with higher site index tend to exhibit greater growth response (Brockley, 2001).

Nitrogen fertilization in lodgepole pine has commonly been applied in forms of urea or ammonium nitrate due to their availability and affordability (Brockley, 1995). Due to the availability of both ammonium (NH_4^+) and nitrate (NO_3^-) forms of nitrogen for uptake, Ammonium nitrate is preferred over urea for operational fertilization in Scandinavia (Brix, 1981). However, in lodgepole pine the effect of these nitrogen sources on stand basal area and foliar nitrogen context depends upon the season of application. While spring applied ammonium nitrate can increase the 1st year foliar nitrogen level, it can also result in higher nitrogen to sulphur ratio (N/S ratio) or increase sulphur deficiency (Brockley, 1995). Similarly, due to high volatilization nature, fall applied urea is not effective for growth increment in lodgepole pine. Due to the uncertainty of effectiveness of nitrogen fertilizers and economic factors related to their large scale applications, more research is necessary regarding the quantity, timing and cost of these fertilizer applications in lodgepole pine in Alberta (Brockley, 2001, 2000, 1990).

Although nitrogen fertilization in lodgepole pine can promote individual and stand level growth, nitrogen only addition in lodgepole pine has resulted in limitation of other elements such as sulphur, boron, calcium, and magnesium, which can limit growth response (Carter and Brockley, 1990). This phenomenon occurs because, in addition to nitrogen, sulphur and boron are also limited in many lodgepole pine stands in Alberta and British Columbia. When nitrogen is added to a site it can elevate other problems. For instance, addition of nitrogen only on a sulphur deficit site can increase the foliar N/S ratio meaning higher nitrogen and lower sulphur available for uptake for plants. This, in turn hinders the protein synthesis process necessary for growth (Brockley, 2000; Carter and Brockley, 1990). To address this issue, one potential solution is to use nitrogen fertilizers that include a blend of other essential nutrients (sulphur, boron, calcium, magnesium etc.). By providing a balanced combination of nitrogen and essential nutrients, the potential negative consequences associated with nutrient imbalances can be mitigated (Brockley, 2001). Another reason for mortality in fertilized stand is due to the accelerated stand development that can provide comparative advantage to the large size trees (Yang, 1985). These large trees often suppress the growth of smaller trees which often undergo density dependent mortality (Moulinier et al., 2015a).

Over the past four decades, extensive research has been carried out to examine the growth response to fertilization in lodgepole pine. Some of key findings of these studies include: i) lodgepole pine has the most variable growth response to fertilization among other conifers in Western Canada, ii) blended fertilizer (nitrogen with other nutrients) is effective for growth benefits iii) and single fertilizations has a short-lived growth increase of up to 8-10 years while repeated fertilizations has a sustained response (Kishchuk et al., 2002). While this research has generated significant insights, there still exist critical knowledge gaps that must be addressed to develop effective operational fertilization programs focused on enhancing future timber supply. A comprehensive review study spanning (40-80) years underscores the importance of conducting key research specifically on late rotation stands of lodgepole pine (Reid et al., 2017).

Although, nitrogen fertilization with other micronutrients has increased growth benefits on 30-70 years old stands in Alberta (Yang, 1985), fertilized stands are also prone to self-thinning due to higher interspecific competition. Therefore, thinning or density reduction is necessary prior to fertilization (Farnden and Herring, 2002; Prescott et al., 2019). For example, a study in natural lodgepole site in BC found thinned and fertilized stand to a density of (2000 trees/ha) had greater stand volume by 77 m^3/ha than fertilized only stand with density of (5000 stems/ha) (Farnden and Herring, 2002). This was because thinning can increase growth efficiency by concentrating limited resources onto fewer trees whereas fertilization can increase resource availability per tree per hectare. This means the trees remained after thinning are benefitted by increased nutrient availability through fertilization (Blevins et al., 2005). From the past studies, it is known that individual tree and stand growth response depends upon the intensity of thinning and fertilization, however operational information on the optimal combination of these treatments in lodgepole pine to obtain best growth response to meet the future timber demand is missing.

1.3. Temporal growth response to thinning

Although, thinning increases individual and stand level growth, this response is not sustained throughout the rotation of a stand. Generally, post thinning growth occurs in phases of reduced growth or no growth in the beginning to increase in growth for some years and lastly phase of declining growth (Valinger et al., 2000). These growth dynamics of thinning are generally studied through two common methods: a) measurement of changes between Diameter at Breast Height (DBH) between two time periods (Das Gupta et al., 2020) or b) using the tree ring analysis to study Basal Area Increment (BAI) (Lockwood et al., 2021). The first method is widely used in Alberta, (Das Gupta et al., 2020; Navratil et al., 2002; Scaria, 2023; Sullivan et al., 2020), with a general finding that thinning increases individual and stand growth compared to unthinned stands and the growth effect of thinning can last for 18 years (Prescott et al., 2019). However, studying periodic increment does not provide an estimation on the temporal phases of growth increment in lodgepole pine. Knowledge about the temporal growth post-thinning can guide forest managers in making silviculture decisions, such as harvesting or follow up thinning plans (Manrique-Alba et al., 2021).

In silviculture, dendrochronology (the science of using tree rings to study past events) has been used as a method to investigate post-treatment effects on trees. This type of study utilizes annual tree ring information obtained from tree cores to examine temporal growth (Lockwood et al., 2021). The general assumption of these studies is that thinning increases radial growth of individual trees because of competition reduction. However, previous studies, have found mixed observations regarding the effects of thinning on growth of conifer trees. For instance, a study on thinned Scots pine (*Pinus sylvestris*) found BAI was greater by 87% in heavily thinned (<1000 trees/ha) and by 50% greater in moderately thinned stands (1000-2000 stems/ha) (Huuskonen and Hynynen, 2006). However, the same species showed contradictory result to thinning in another study (Plauborg, 2004). These differences in growth outcome occurs due to the level of competition before thinning (where growth is higher for stands with high competition), the age at thinning (which influences radial growth and tends to be higher in young trees) (Peltola et al., 2007), and suppression history of thinning (wherein growth is higher for dominant and co-dominant trees) (Baral et al., 2016). Therefore, analyzing these varying results and the factors influencing radial growth post thinning is necessary to gain a comprehensive understanding of the effects of thinning on conifer trees.

Tree size is a significant factor affecting the post thinning radial growth in conifer species of varying shade differences including white spruce, white pine, Scots. pine, jack pine (Jones et al., 2009; Masaka et al., 2013; Mehtatalo et al., 2014). Growth response of small trees to thinning occurs in stand, where larger trees have already acquired relative position in the canopy with high exposure to crown (Jones et al., 2009; Mehtatalo et al., 2014) and gaps created by thinning allows growth of these small trees. However, if the small trees have been suppressed for a long period of time, then thinning induces growth of co-dominant or medium size trees (Baral et al., 2016). While growth of small to medium trees occurs in stands with demand for light, thinning increases the growth of larger trees limited by nutrients (Stanturf et al., 2003). However, this information is lacking in lodgepole pine, as there are limited studies that look at temporal effect of thinning on trees of different sizes. This information is necessary for prioritizing thinning operations in lodgepole pine stands in Alberta.

1.4. Study objectives

The main research question of the study is to understand the individual and stand level growth response of 88-year-old lodgepole pine to commercial thinning and nitrogen fertilization individually and in combination. This objective is discussed in detail in the second chapter (Chapter II) of this document. This chapter used a long-term (20 years) dataset to answer the research question. The Chapter III of this document corresponds to a field study that uses the 20 years tree core data to study the temporal growth effect of thinning in trees of different size classes. The Chapter IV of this document contain the summary and conclusion of the thesis as well as provides management implications for future practices.

CHAPTER II: COMMERCIAL THINNING & FERTILIZATION IN LODGEPOLE PINE: A 20 YEAR RESPONSE ON GROWTH

2.1. Introduction

Timber plays a crucial role in Canada's economy, with exports worth $45 billion dollars in 2021 (Natural Resources Canada, 2021). However, a potential timber supply reduction is forecast in the near future due to the cumulative effect of fire, insect outbreaks, drought, and the allocation of forest land to other industrial uses (Boucher et al., 2018). Intensive silviculture practices such as commercial thinning and fertilization have increased timber productivity in boreal conifers (Ward and Erdle, 2015; Stanturf et al., 2003) and may help to sustain timber supply while maintaining the flow of second-growth timber with the required size and quality and supporting the smooth operation of forest-based industries that are in the front line for management (Pinno et al., 2021).

Commercial thinning is an intermediate harvest in even-aged stands, used mid to late-rotation to achieve benefits like immediate timber extraction, capturing volume that would otherwise be lost to mortality, and promoting stand and individual tree growth (Bose et al., 2014; Rowan, 2012). Commercial thinning has been shown to boost growth up to 31% in North American conifers like loblolly pine, jackpine, balsam fir etc. and maintain productivity throughout the life cycle of the forest (Bose et al., 2018a) by increasing the growth of residual trees and decreasing the competition for above and below ground resources (light, nutrients, and water). Forest fertilization is another intensive silviculture treatment conducted to improve tree growth and maximize stand yield (Garrison et al., 2000). Fertilization increases resource availability and promotes individual tree growth (Brockley, 2001). Thinning and fertilization treatments complement each other at the individual and stand-level. Thinning reduces stand-level volume and leaf area, which is needed for light absorption and stem wood production, but thinning also reduces competition for resources providing space for crown and radial expansion (Blevins et al., 2005). In contrast, fertilization increases light use efficiency, photosynthesis rates and allocation of carbon for stem wood production (Bergh et al., 2014). Therefore, thinning and fertilization are often combined for greater individual tree and stand-level responses (Moulinier et al., 2015b). However, these intensive silviculture treatments are not commonly practiced in the public lands of Alberta which are also the major industrial wood source of the province (Pinno et al., 2021).

Lodgepole pine (*Pinus contorta* var. *latifolia*) is among the most important commercial species in western Canada (Prescott et al., 2019) with pure lodgepole pine stands making up 46% of the land base in the foothills regions of western Alberta. Commercial thinning has the potential to shorten individual stand rotation length meaning provide early access to fiber, and sustain the supply of second-growth timber by increasing cumulative merchantable volume in lodgepole pine (Das Gupta et al., 2020; Navratil et al., 2002). At an individual level, commercial thinning increases the size DBH of individual trees consequently increasing volume. This can reduce the processing and harvesting costs during final felling as larger trees make more volume/tree and less handling cost(Kuehne et al., 2018). This tree level growth response has shown to be size-specific that benefits large and medium-sized trees due to their higher capacity to uptake light and nutrient for growth (Peltola et al., 2007). Apart from improving growth and productivity, commercial thinning can also increase resistance to disturbances like mountain pine beetle and wildfire (Mitchell et al., 1983; Whitehead et al., 2007) by reducing dead and weak tress that also make fuel load on the stand. Commercial thinning can also create old-growth structural attributes in a forest such as large dominant trees, gaps and multi-layer in the canopy, understorey patchiness etc. (Sullivan and Sullivan, 2016) and improve post drought recovery and resilience by making water resource available to few trees (Sohn et al., 2016)

Lodgepole pine forests in western Canada are often nutrient deficient with nitrogen being the most common limiting nutrient, along with boron and sulphur (Brockley, 2005, 2001; Cook et al., 2015). Thus, stand and tree-level productivity may be increased by application of nitrogen and micronutrient fertilizer (Blevins et al., 2005; Kishchuk et al., 2002; Brockley, 2001). For example, a study on 8 year old lodgepole pine showed a 38% increase in mean tree basal area and 42% increase in mean tree volume by repeated application of 150 kg/ha N with a blend of nutrients after 14 years in British Columbia (Kishchuk et al., 2002). However, empirical research have shown, the growth response of lodgepole pine exhibits a wide range of outcomes, demonstrating significant variability depending upon, stand age, frequency of application, fertilizer combination, stand density, and site index (Reid and Prescott, 2017). Therefore, it is crucial to carefully consider these variables when designing fertilizer application strategies to optimize the growth and productivity of lodgepole pine forests.

Nitrogen fertilizer in Canadian forests has commonly been applied in the form of urea ($CO(NH_2)_2$) due to its availability and affordability. However, lodgepole pine has shown increased growth response to ammonium nitrate (NH_4NO_3) due to the high availability of nitrogen in the form of ammonium and nitrate (Brockley, 1994). Although nitrogen is the primary nutrient deficient in lodgepole pine growing sites, other micronutrients such as sulphur, boron, calcium and magnesium (Carter and Brockley, 1990) can also be limiting. These limitations can also be exacerbated by nitrogen addition, so in some situations a balanced combination of nitrogen with essential nutrients is necessary for optimal response (Brockley, 2000).

Studies conducted over the last 40 years have provided considerable information on growth response to thinning and fertilization on lodgepole pine. For example, thinning and fertilization with nitrogen and other nutrients increased individual DBH growth by 0.6 cm in three years on 6-22 year old lodgepole pine stands (Pinno et al., 2012) while in a mature stand of 40 years, combined thinning and fertilization treatment increased DBH by 0.4 cm/year, while individual treatment thinning only increased by 0.25 cm/year and fertilization alone by 0.13 cm/year (Blevins et al., 2005). However, further information is needed on late-rotation stands for making recommendations at an operational scale (Reid et al., 2017). These information gaps can be addressed by conducting follow up studies on commercial thinning and fertilization on established trials in Alberta during early 2000s (Dempster, 2001) .This study utilizes the data from established experimental trails in Alberta and is based on the key objective of assessing the long-term response of commercial thinning and fertilization (single or in combination) on stand-level growth, individual tree-level growth, and mortality.

2.2. Methods

The experiment was installed in the spring of 2000 in what was then a 68-year-old, fire-origin lodgepole pine stand, located in the Upper Foothills Natural Subregion of Alberta, Canada, (53.399°N -117.071°W) on lands currently managed under a Forest Management Agreement (FMA) between West Fraser Mills Ltd. And the Government of Alberta (Alberta Environment., 2006). At the establishment, the foliar nutrient status was assessed, and the nitrogen concentration was 1.01% which indicated a severe deficiency and the site index was 15 (Dempster, 2001). Moderate deficiency of other nutrients was assessed, with foliar concentrations of phosphorous (0.16%), magnesium (0.09%), potassium (0.4%), sulfur (0.09%), and boron (32.5 ppm) (Dempster, 2001).

The experimental layout uses a balanced 2 by 6 factorial designs as a partial split plot in a randomized complete block design (Figure *1*). There were three blocks with two sub-blocks for: 1) Commercial thinning with 50% basal area removal and 2) Unthinned. Nitrogen fertilizer was applied randomly to six plots within each of the sub-blocks in forms of Urea ($CO(NH_2)_2$) or Ammonium nitrate (NH_4NO_3). Urea fertilizer levels were : a) 200 kg/ha N+ 3 kg/ha Boron, b) 200 kg/ha N + blend c) 400 kg/ha N + 3 kg/ha Boron and d) 400 kg/ha N+ blend) and Ammonium nitrate level was e) 400 kg/ha N + Boron. The remaining plots had No fertilization control. The blend fertilizer was mix of phosphate, sulphate, magnesium, and borate. Each of the blocks were further divided into treatment plots of 52 m × 40 m in the thinned plots and 40 m × 40 m in the unthinned. Each treatment plots further had an inner 20 m × 20 m measurement plots with 10 m fertilized buffer on all sides.

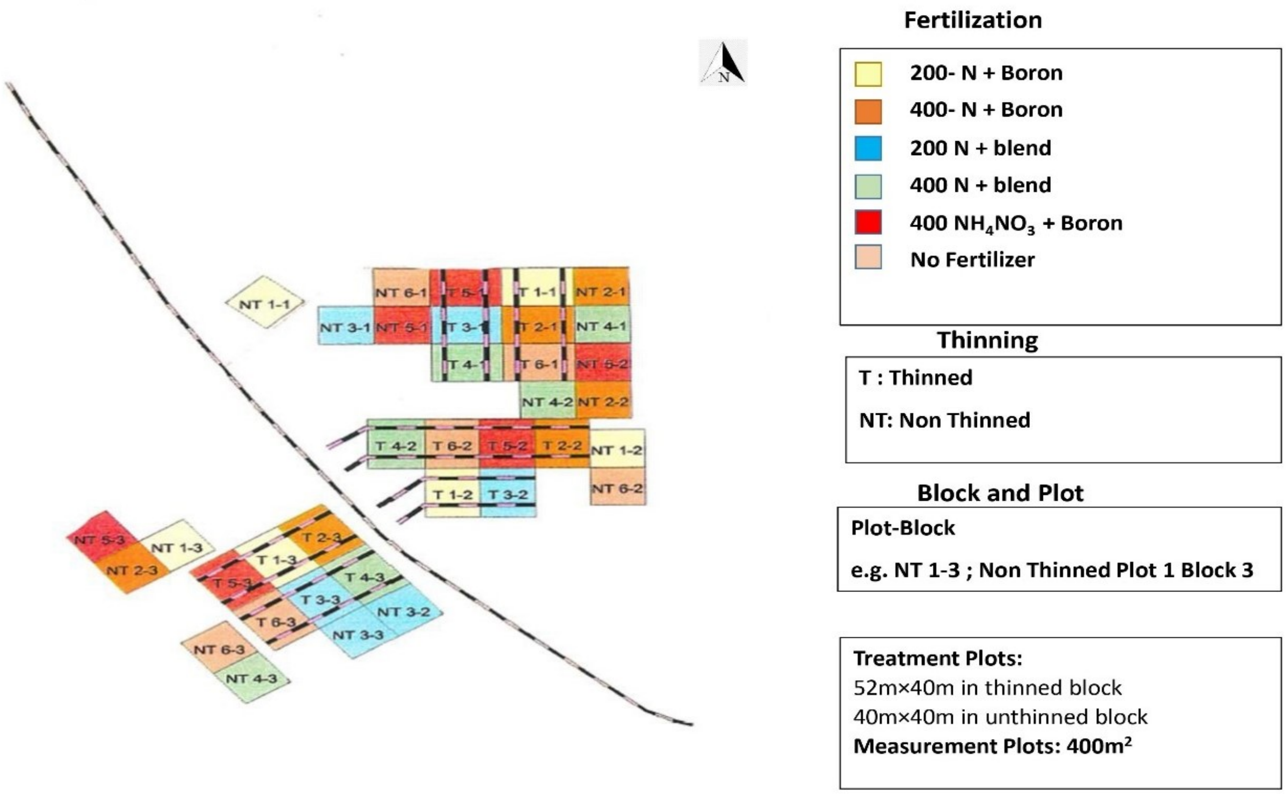


Figure 1. Split plot factorial experimental design of the study area. The source of the figure is (Dempster, 2001)

The commercial thinning prescription adopted for the site was a target of 50% basal area (~19 m^2/ha) removal. All trees were removed along forwarding trails with the remaining forest matrix thinned from below removing the smaller diameter trees and retaining healthy trees until the desired basal area removal was reached. A total volume of 96 m^3/ha and a merchantable volume (total volume minus the stump and top volume) of 70 m^3/ha was removed during thinning. This maintained an average of 1680 trees/ha. The thinned and unthinned plots had no difference in diameter (11.1 cm) or height (15.2 m) prior to treatment while post-thinning mean diameter for thinned plots increased to 12 cm. All live trees in the measurement plots were measured in the year 2000 after the treatment and assessed again in 2021. Measurement at the individual tree level included DBH, height, height to live crown, and crown diameter. DBH was measured at 1.3 m, height is the total height from base to the tallest live portion of crown, and height to live crown was measured from the ground to base of live crown. Base of live crown was set at the lowest reaching point of the lowest branch. Plot-level attributes derived from tree measurements include included basal area (m^2/ha), merchantable and total volume (m^3/ha), and quadratic mean diameter (cm). The status of each tree (live or dead) was recorded during the initial and final measurement period. For the stand-level assessment, basal area, total volume, and merchantable volume of the trees were calculated using Forestry Toolbox, an Ms. Excel add-in for forestry data analysis (FGROW, 2022) that uses equations developed in Alberta by (Huang, 1994) for volume calculation. For merchantable volume, the 15/10 merchantability criteria were used, where 15 cm is the minimum diameter outside bark at 15 cm stump height of a merchantable tree and 10 cm is the top diameter inside bark. Cumulative volume was calculated as the sum of merchantable volume removed at thinning and the standing volume at present. Top height was calculated as average height of the 100 largest diameter trees/hectare for each treatment unit. Individual crown volume was calculated as volume of ellipsoid derived from (Zhu et al., 2021).

Individual tree and stand-level growth was calculated as periodic increments between 2000 and 2021 and treatment differences were determined using Analysis of Variance (ANOVA). The merchantable DBH of trees in this study is 13.4 cm and 20 cm DBH trees are considered as trees that make good saw log (Hossain et al., 2022). Trees were divided into 5 cm interval diameter classes starting from 5.1 cm to 30 cm for assessing the diameter distribution of trees.

Analysis of Variance (ANOVA) was performed to determine the effect of thinning (T) and fertilization (F) on growth and mortality. As the experiment was a split plot analysis, block and thinning treatments were considered as an error term (Dempster, 2001). Mixed model type III ANOVA was conducted to access the effect of initial tree DBH (diameter during thinning) on growth of individual trees. Overlap of confidence interval of individual treatments (thinning and fertilizer) at different size class was used to find the most responsive size to the treatments. Relative mortality and merchantable tree density was compared between the thinning and fertilization treatments.

Specific pairwise comparisons with Bonferroni corrections were conducted to compare differences between No fertilizer and fertilization levels, within 200 kg/ha N levels and 400 kg/ha N levels. Boron vs. blend fertilization were compared at respective 200 and 400 levels.

2.3. Results

Standing merchantable volume at age 88, 20 years after treatment, was higher in unthinned plots than in thinned plots by 32 m^3/ha (F=4.32, p=0.04, Figure 1). However, cumulative merchantable volume (standing merchantable volume + volume removed at thinning) was greater (F=3.67, p=0.04) in thinned stands. Standing merchantable volume also differed with fertilization levels (p<0.01; Table A1) and was highest with 400 kg/ha Ammonium nitrate+Boron of 204 m^3/ha (Table A2). Post-treatment basal area growth was similar across treatments at 10.1 m^2/ha (thinning p=0.79, F=0.65, df=1, fertilization p=0.68, F=0.62, df=5). Total density was greater (F=16.8, p<0.001, Figure 2) in unthinned plots (3218 trees/ha) than thinned plots (1624 trees/ha) while the proportion of sawlog trees >20 cm is greater in thinned plots than unthinned plots (F=23.869, p=0.039) by 20% (Figure 3).

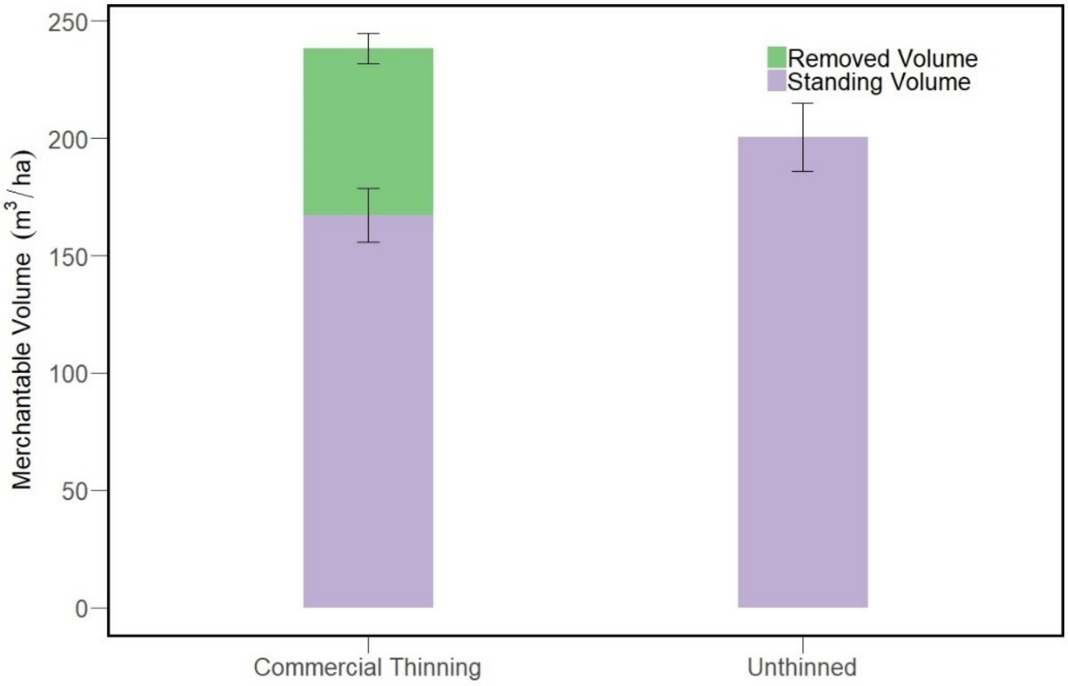


Figure 2. Standing merchantable volume in thinned and unthinned plots with merchantable volume removed while thinning at thinned plot. The error bars indicate standard error.

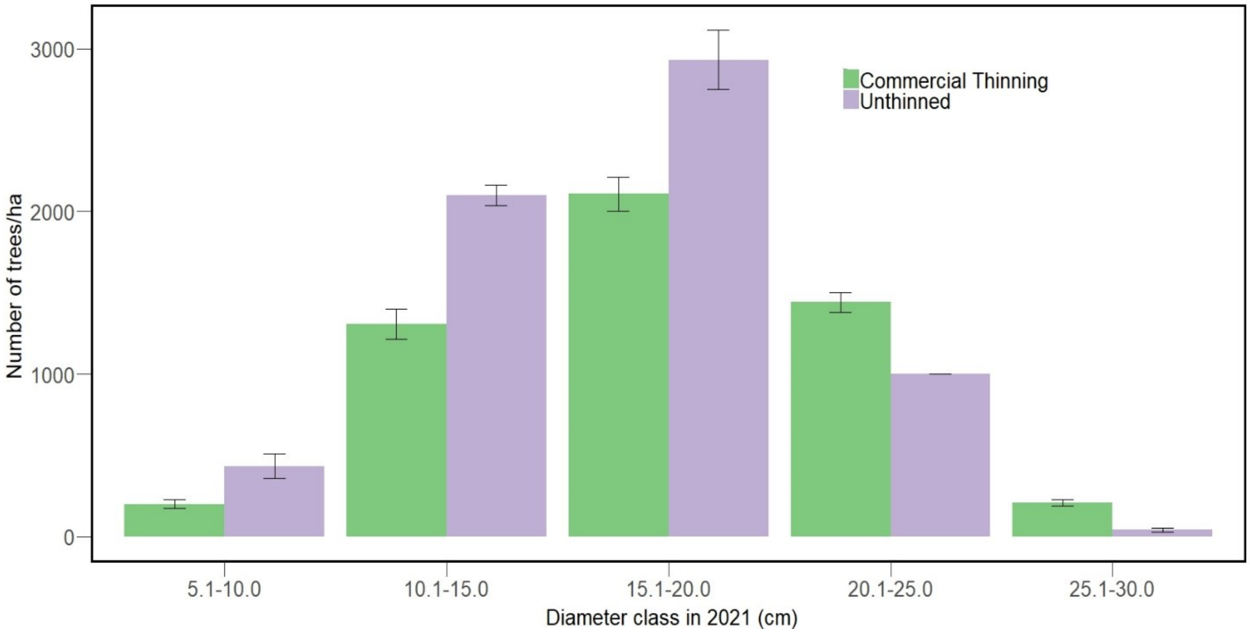


Figure 3. Diameter distribution of the thinned and unthinned plots. The X-axis represents diameter distribution of trees twenty years after thinning and y-axis represents density of trees per hectare. The error bar represents standard error.

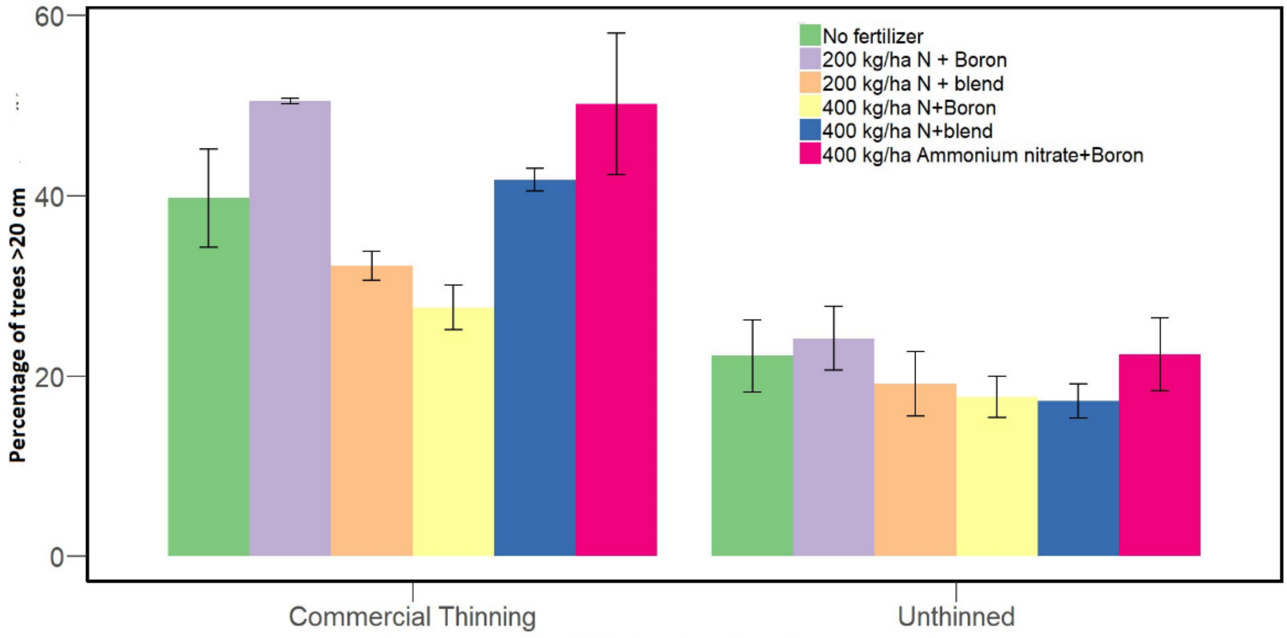


Figure 4. Proportion of saw log-sized trees by treatment. The X-axis represents thinning treatments and Y-axis represents the percentage of saw log trees. Error bars represent +/-1 standard error.

Table 1.Summary of stand level properties of the stands 20 years post-treatment; CT=Commercial Thinning, UT=Unthinned, QMD= Quadratic mean diameter; TPH= Trees per Hectare

Treatment		**Stand Attributes in 2021 (age 89)**					
Thinning	Fertilization	Merchantable volume removed in 2000 (age 68; m^3/ha)	Density (TPH)	QMD (cm)	Standing Merchantable volume (m^3/ha)	Top height (m)	Crown volume (m^3/ha)
CT	No fertilizer	65.1	1383	16.81±1.1	166.7±4	17.7±1.2	24.6±0.16
	200 kg/ha N+ Boron	65.2	433	18.8±3.8	150.8±04	17.4±2.1	26.1±0.1
	200 kg/ha N +blend	56.6	1175	18.2±2	176.3±11	16.2±0.6	28.5±0.1
	400 kg/ha N+Boron	77.9	1300	18.1±1.7	151.7±11	17.7±2.2	34.8±0.2
	400 kg/ha N + blend	68.7	1067	18.7±2.3	157.8±12	16.9±1.4	39.3±0.2
	400 kg/ha Ammonium nitrate+ Boron	90.6	1183	19.4±3.6	202.9±19	16.7±2.5	45.3±0.3
UT	No fertilizer	-	2775	19.3±4.2	225.5±09	17.2±1.4	31.3±0.1
	200 kg/ha N+ Boron	-	2242	14.1±1.4	147.4±06	17.5±1.8	27.6±0.2
	200 kg/ha N +blend	-	2233	18.3±1.3	206.5±14	17.2±1.2	22.8±0.1
	400 kg/ha N+Boron		2175	14.4±1.2	188.7±16	17.3±2.4	27.6±0.2
	400 kg/ha N + blend	-	2200	19.0±3.6	225.5±23	17.1±1.6	31.6±0.1
	400 kg/ha Ammonium nitrate+ Boron	-	1958	19.8±3.8	204.7±20	17.2±1.9	38.2±0.7

Individual tree DBH growth since thinning was greater in thinned (4.32±0.2 cm) than unthinned plots (3.39±0.05 cm) (F=8.034, p=0.04, Figure *4*). Within fertilization treatments, DBH growth was highest at 400 kg/ha fertilization level with mean value 4.2 cm followed by 200 kg/ha N+blend of 3.4 cm, Control of 3.1 cm and 200 kg/ha N+Boron of 2.95 cm (F=3.55, p=0.01). There was no difference in growth between nitrogen sources (urea vs. ammonium nitrate) at the 400 kg/ha level (p=1) or between boron vs. blend at either the 400 or 200 kg/ha N levels (p>0.05) in all cases. DBH Growth of individual trees on fertilized thinned plots were higher than fertilizer unthinned (F=4.024, p=0.01).

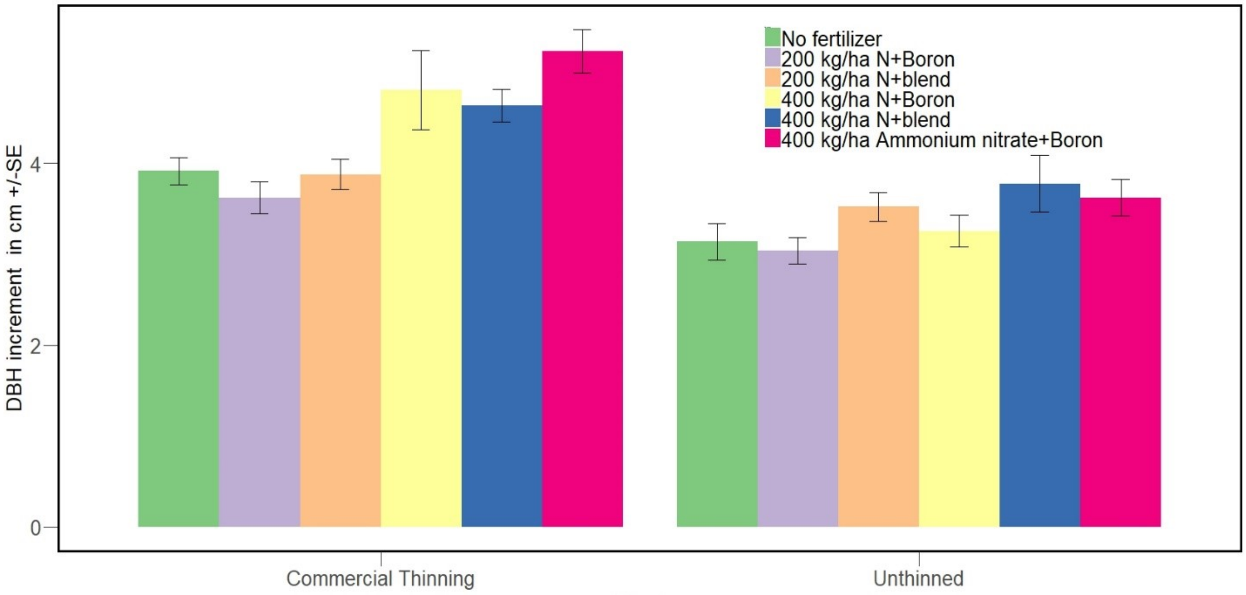


Figure 5. DBH growth of individual trees twenty years after treatment in thinned and unthinned plots. Error bars indicate standard error.

Initial DBH is a strong positive predictor of DBH growth (F=178, p<0.001), and the relationship was statistically different among treatments (Figure 6; Table A2). Commercial thinning resulted in increase in the diameter increment for the control and the three 400 kg/ha N treatments, though the differences were dependent on the initial DBH. In contrast, there was little if any difference in diameter increment between control and thinned for the two 200 kg/ha N treatments. Only the 400 kg/ha ammonium nitrate + boron treatment resulted in consistent increases in increment across the entire range of initial DBH.

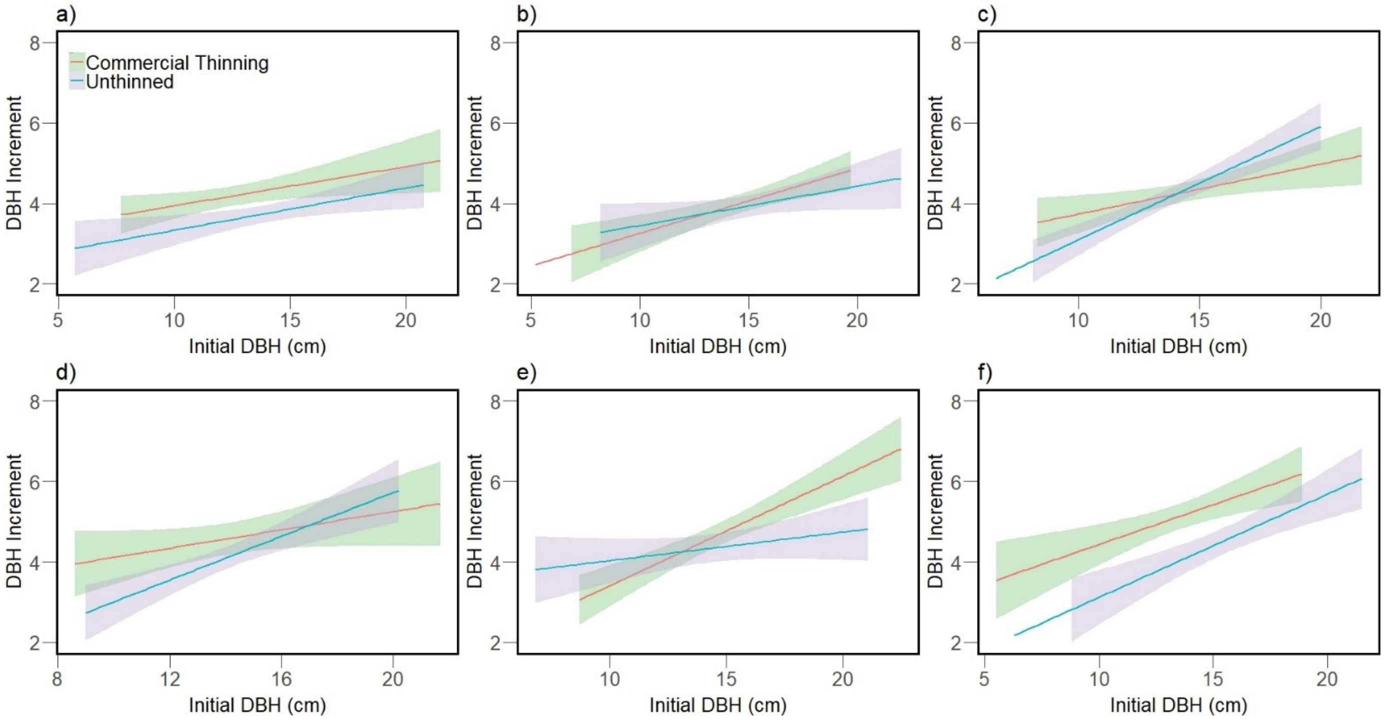


Figure 6. Growth of thinned and unthinned trees of different sizes at the six fertilization levels a) No fertilization b) 200 kg/ha N+Boron c) 200 kg/ha N+blend d) 400 kg/ha N+Boron e) 400 kg/ha N+blend f) 400 kg/ha Ammonium nitrate+Boron. The X-axis represents the DBH of trees at the time of thinning and Y-axis represents growth in 20 years period.

There are more dead trees (2022 trees/ha) in unthinned compared to thinned plots (758 trees/ha) (F=33.157, p=0.02) with mortality in unthinned plots greater than 50% (Figure *7*. Proportional mortality of trees on thinned and unthinned plots. Error bar indicates standard errors.. Mortality increased with fertilization level (F=1.657, p=0.0041) and is higher in unthinned plots (F=2.12, p=0.03). Thinned and unfertilized plots have the least mortality of 36%.

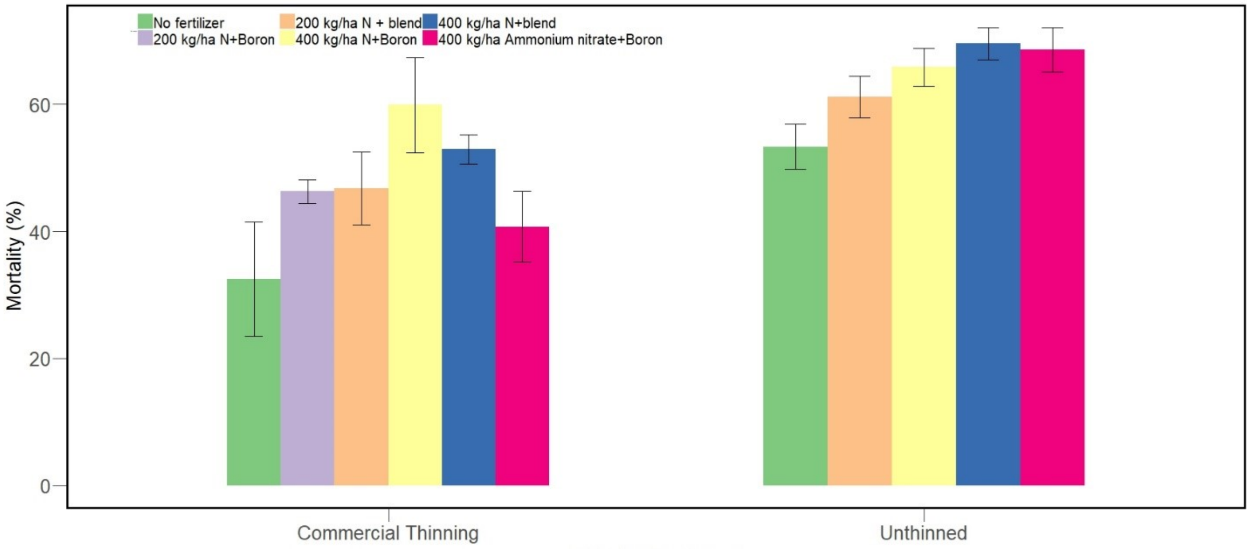


Figure 7. Proportional mortality of trees on thinned and unthinned plots. Error bar indicates standard errors.

Merchantable tree mortality is higher in the unthinned plots (425 trees/ha) than in thinned stands (195 trees/ha) (F=12.412, p<0.001).

2.4. Discussions

Finding of the study confirms, commercial thinning alone or in combination of nitrogen fertilizer can increase timber production and stand value of natural lodgepole pine stands in the upper foothills of Alberta even at a late rotation stage (68- years old). Our study adds an important piece of information that commercial thinning an be effective in increasing stand merchantability even in poor sites and natural stands. The merchantability of the stand is increased by commercial thinning as the cumulative merchantable volume yield from the thinned plots surpassed the unthinned plots in two decades, relaxing growth suppression and capturing mortality. This means commercial thinning can provide a sustainable supply of the second growth timber throughout the rotation stage in Alberta. These results add and strengthen the body of evidence for the potential value of commercial thinning also backed up by (Das Gupta et al., 2020), who found cumulative merchantable volume to be greater by $27m^3$ in 50 years old lodgepole pine after 15 years. In Alberta thinning is recommended on good sites to produce more merchantable volume.

Another advantage of commercial thinning was recruitment of more trees into larger size class as shown by 20% higher density of trees (>20 cm). This increase in large size trees as result to thinning means more efficient harvesting operations and increase the stand value, (Hossain et al., 2022).The basal area growth between thinned and unthinned plots is similar implying increased growth of individual trees was able to recover the basal area increment lost due to reduction in density from thinning.

Commercial thinning has increased individual tree DBH growth over the 20 years that has lapsed since the thinning treatment. This benefit of thinning on residual trees is through reduction in competition for above and below-ground resources and providing space for crown expansion, widely recognized in lodgepole pine and other conifers in North America (Bose et al., 2018b; Gauthier and Tremblay, 2019; Moulinier et al., 2015b; Navratil et al., 2002). These finding of individual tree and stand growth hold significance for Alberta and have the potential to influence a change in the perception among policymakers that intensive silviculture treatments, such as commercial thinning, can be uneconomical.

Initial tree size is the predictor of future DBH growth but the greatest DBH growth response to thinning was shown by small to medium trees upto (~15 cm) in unfertilized control likely because of release from competition from larger dominant trees. Release from competition had no growth effect on the largest or smallest diameter classes. The largest trees, they were already accessing the available resources so thinning made no difference for resource acquisition (Das Gupta et al., 2020) while the smallest trees were further suppressed by the increased growth of co-dominant trees resulting in no increased growth of the smallest trees. This finding supports the principle that thinning favors growth of dominant and co-dominant more than suppressed trees (Johnstone, 2002).

Preliminary foliar analysis of the research site indicates severe deficiency of nutrients mostly nitrogen and boron. We assume competition for above and belowground resource and can be limiting the growth of small and medium trees. Therefore, small, and medium trees that receive fertilization with nitrogen and boron along with competition removal showed increased growth response. Higher fertilization level, i.e. >400 kg/ha is beneficial because higher fertilization increases the availability of nutrients in the soil for uptake by plants that support growth (Brockley, 2005; Kishchuk et al., 2002).

Fertilization studies in lodgepole pine have recommended use of blended fertilizers with mix of micronutrients like (sodium, calcium, boron, magnesium) due possible concern about secondary nutrient deficiency after nitrogen addition (Brockley, 2000). However, in this case individual (DBH) growth response also did not differ due to the fertilization combination such as (boron vs. blend) or (urea vs. ammonia). Possible reason why the significant difference was not observed is because this study was a single fertilization study, and a remeasurement was conducted 20 years later, after the response periods of urea (6 years) and Ammonium nitrate (7-10 years) had surpassed (Valinger et al., 2019).

Mortality was reduced by thinning but increased by fertilization. Thinning was able to minimize density dependent mortality occurring due to intraspecific competition from neighboring trees and self-thinning (Peet and Christensen, 1987). One of the criteria for thinning in this study was to remove unhealthy, damaged, and less vigorous trees, which are most vulnerable to mortality. Fertilization-induced mortality is likely attributed to the preferential growth promotion of medium and large trees, which creates a significant size discrepancy. Consequently, medium to large trees have better access to nutrients compared to smaller trees, resulting in their increased mortality (Moulinier et al., 2015b). Additionally, studies by (Farnden and Herring, 2002) have reported increased mortality in lodgepole pine when fertilization levels exceed 400 kg/ha N, as it intensifies competition for belowground resources that primarily support medium and large trees.

However, the effect of fertilization on growth and mortality was contingent on thinning. For example, diameter growth of individual trees was higher at thinned and fertilized plots (Figure 5) and (Figure 6) but mortality was higher in fertilized and unthinned plots (Figure 7). Other studies on lodgepole pine (Farnden and Herring, 2002; Yang et al., 1988) also report better growth can be obtained when fertilization is combined with thinning rather than applying them individually. This is because thinning alone, reduces competition and redistributes space for residual trees in contrast fertilization increases nutrient availability for take up by residual trees due to an increase in foliage biomass and photosynthetic efficiency of that foliage (Brockley, 2005; Sullivan et al., 2020a).

Commercial thinning alone or in combination with nitrogen fertilizer, can be chosen as a potential silviculture treatment to address the impending timber supply issue in Alberta. Our findings show in a natural stand, where thinning is conducted at a late rotation (68 years), commercial thinning can increase DBH growth by 1.3 times resulting in greater cumulative volume and proportion of saw logs by 17% than in unthinned stands. In case of fertilization, the 400 kg/ha N has better growth results than the 200 kg/ha levels. On an average, the 400 kg/ha nitrogen fertilization increased DBH growth by 1.13 times, however reduced the total merchantable volume by 19.2 m^3/ha due to the increased mortality of 14.7%. Best results of fertilization is achieved, when combined with thinning. Commercial thinning and 400 kg/ha nitrogen fertilization increased the growth of individual trees by 1.56 folds and cumulative merchantable volume by 24.6 m^3/ha. Based on these findings, it is advisable to consider and further evaluate the use of commercial thinning along with nitrogen fertilizer as a potential solution to the timber supply issue in Alberta.

CHAPTER III: POST-THINNING TEMPORAL GROWTH DYNAMICS IN LODGEPOLE PINE: A SIZE-DEPENDENT ANALYSIS ACROSS TWO DECADES

3.1 Introduction

The forest resource of Alberta is predicted to be impacted by short to midterm decline in timber supply due to cumulative effect of wildfires, insect infestation, drought, and conversion of forest area into other land uses (Gauthier et al., 2015; Pinno et al., 2021b; Price et al., 2013). To tackle this mid-term wood supply crisis, one approach is a shift from traditional reforestation practices to more intensive management that enhances the growth of residual trees and the stand (Griess et al., 2019; Pinno et al., 2021a). Commercial thinning is a component of intensive management that reduces competition and reallocates above and below ground resources to residual trees. This promotes individual tree and and overall stand level growth thereby, increasing financial returns from the forest stands (Bose et al., 2018a; Gauthier et al., 2015). This phenomenon has been well observed in boreal conifers across Canada.

Although thinning increases individual tree growth, the post thinning growth may not be sustained throughout the rotation period. Post thinning growth generally, occurs in three distinct phases: a) initial phase of no-growth or reduced growth, b) second phase of growth increment and, maximization, and c) the final phase of growth declination (Valinger et al., 2000). The first phase of reduced growth is due to a physiological phenomenon called thinning shock, caused due to stress in trees by sudden change in growing environment (e.g. light, micro-climate, nutrient availability) and can last for a period of 2-5 years in most boreal conifers stand.

The second phase of growth increment depends upon several reasons such as age, thinning intensity, species, and tree size (Girona et al., 2016). The different growth rates relative to individual size is known as growth dominance (Chen et al., 2022), and is higher for larger trees due to their capacity to uptake light and nutrient for growth, besides thinning also increases size asymmetric competition (Peltola et al., 2007). Post thinning growth in conifers have found thinning treatment usually lasts for a period of 10-25 years. For example, it is 13-14 years in *Pinus nigra* with basal area (30 m^2/ha), 9 years in heavily thinned (70% basal area removed) in *Pinus pinaster* (Aldea et al., 2017). .

Lodgepole pine is a native conifer species to Alberta contributing to 26% of the total growing stock in the province (Alberta's Forest Economy, 2021). Like other conifers in Canada, thinning in lodgepole pine has been growth promotive at a) individual and stand level (Das Gupta et al., 2020), b) natural and plantations and c) young and mature stands (Johnstone, 2002; Prescott et al., 2019). Short- and long-term thinning studies found thinning response in lodgepole pine can last upto 18 years (Prescott et al., 2019). However, these responses were accessed on basis of periodic measurement of individual tree diameter at temporal intervals. So far, information of temporal response to thinning and how this factor differs according to the pre-thinning characteristics is lacking in Alberta.

Evaluating the temporal growth in lodgepole pine provides an opportunity to observe the thinning response over time allowing practitioners to assess the persistence of management practices. This includes determining when maximum growth rates are achieved after thinning, observing the subsequent decline in growth, and understanding the long-term benefits of thinning throughout the rotation period (Manrique-Alba et al., 2021; Soucy et al., 2012). The post-thinning growth information can be integrated into forest harvesting management and used for long-term planning of timber supply. This is crucial within the context of forest sustainability, as it helps reconcile ecosystem management and wood production goals (Girona et al., 2016).

To characterize this temporal growth dynamics, use of tree ring analysis is recommended (Swetnam et al., 1985). Tree ring analysis involves involves analyzing the annual growth rings in tree cores, which provides insights into past and current growth patterns of individual trees (Lockwood et al., 2021). By applying this method, the following questions are addressed in this studies : a) What is the temporal effect of commercial thinning in lodgepole pine? b) Does any observed growth effect vary by the size class of trees?

3.2. Methods

The experiment was installed in the spring of 2000 in what was then a 68-year-old, fire-origin lodgepole pine stand, located in the Upper Foothills Natural Subregion of Alberta, Canada, (53.399°N -117.071°W) on lands currently managed under the Hinton Forest Management Agreement (FMA) (Alberta Environment., 2006). The experiment was designed as a factorial experiment with three blocks, and two sub-blocks for thinned and unthinned. The treatment plots in thinned sub-blocks were 52 m ×40 m and in unthinned sub-blocks 40 m ×40 m. Each of the treatment plots further had an inner 20 m ×20 m measurement plot.

The commercial thinning prescription adopted for the site was 50% basal area (~19 m^2/ha) removal. All trees were removed along forwarding trails with the remaining forest matrix thinned from below removing the smaller diameter trees and retaining healthy trees until the desired basal area removal was reached. A total volume of 96 m^3/ha and a merchantable volume (total volume minus the stump and top volume) of 70 m^3/ha was removed during thinning. This maintained an average of 1680 trees/ha. The thinned and unthinned plots had no difference in diameter (average = 11.1 cm) or height (average = 15.2 m) prior to treatment while post-thinning mean diameter for thinned plots increased to 12 cm.

In the summer of 2022, 10 trees were randomly selected from three blocks of thinned and unthinned plots making a total of 30 trees. The DBH of individual trees was measured at 1.3 m above the ground surface. Individual tree heights were measured as the total height of the tree using a clinometer. The mean DBH of thinned plot was greater than unthinned plots by 3.7 cm. The basal area of the thinned and unthinned plots were similar of 25.4 m^2/ha and the standing merchantable volume was greater in the unthinned (225m^3/ha) than in the thinned plots (166.7 m^3/ha).

Two cores per tree at breast height (1.3 m) were collected in perpendicular directions using 12-mm Pressler increment borers. Careful consideration was given to avoid any breakage of the cores. Trees were re-cored if the cores were broken into more than three pieces. The cores were then stored in straws with flags indicating the plot and tree numbers for reference. After bringing to the lab, the tree cores were dried in the oven at 70°C for 72 hours to ensure the moisture content was reduced to less than 5% which is considered stable for further processing (Girona et al., 2016). After the cores were dried, they were carefully examined for any kind of damage, cores whose damages could not be fixed while mounting was screened out. The dried cores were then mounted on a wooden core mount using gorilla glue and the unique identification number (block, plot, treatment, tree id, and core id) was written on the board. The cores mount board was made up of 1.3 cm thick birch plywood with 5 slots precisely 5.5 mm wide and 3 mm deep. Then the cores were sanded using a belt sander with 120-300 grit paper until the rings were visible. This process is also shown in (Figure 8).

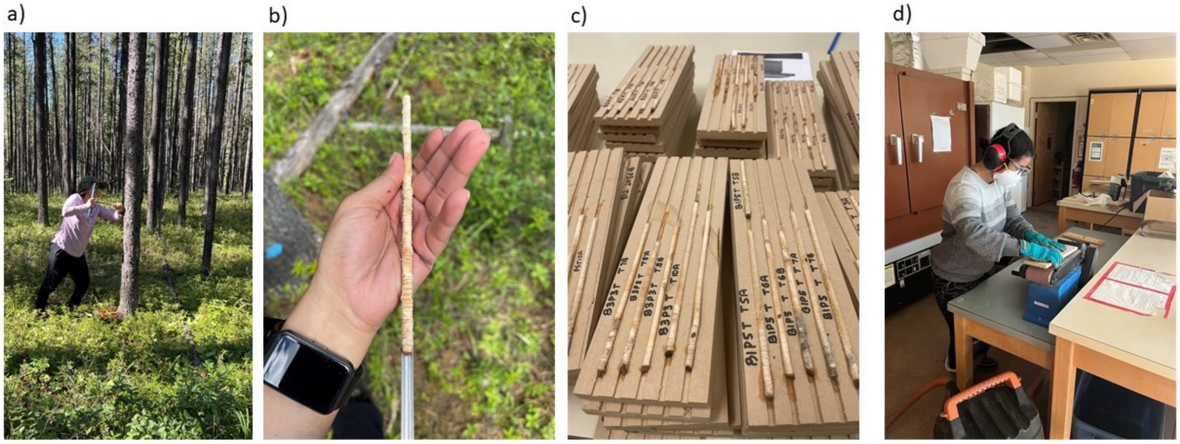


Figure 8. A stepwise description of tree core extraction and preparation for analysis. a) Method of increment borer insertion into a tree. b) Extraction of tree core from the borer c) Mounting of cores into the board d) Sanding the cores

Sanded tree cores were visually cross-dated using the C.Dendro and CooReader software R. The ring width series of each of the cores were measured to the nearest 0.001 m. The tree ring values were then converted to the BAI value. BAI is the change in cross sectional area associated with each annual ring and is the most closely linked measure of the biomass increment (Lockwood et al., 2021). To avoid field sampling error mainly due to failure of the core to reach the piths, the BAI was calculated using the field collected DBH and the following steps (Linares and Tíscar, 2010).

Step 1: Conversion of tree DBH to the radius, R=DBH/2

Step 2: Calculation of the Radius Inside Bark (RIB)= R-Bark Thickness measured on the core

Step 3: Calculation of implied core length for the last year (CL) = RIB-Ring Width for the year

Step 4: Calculation of the Basal Area for the year BAnth year= $\pi * CL^2$

Step 5: Basal Area Increment (BAI)= $BAI_n - BAI_{(n-1)}$

Data analysis was conducted using the R and R Studio Version 4.3.0. To study the relation of individual tree size on growth, trees were divided into four diameter classes with 2.5 cm intervals based on their diameter at thinning in 2000. Dividing trees into size class has been a commonly adopted method to study the relationship between tree size and growth in other radial growth studies of conifers (Jones et al., 2009; Peltola et al., 2007). Besides, the results from Chapter II also shows, individual tree size at thinning is a significant predictor for growth, so to better understand the size related growth, we decided to classify the trees into the following classes a) 10.1-12.5 cm, b) 12.6-15 cm, c) 15.1-17.5 cm, and d) 17.6-20 cm. The time series was also divided into 5-year periods to study the temporal response of trees to treatments. In this analysis we have used data before 5 years of treatment and 20 years after treatments divided into periods, pre thinning (1995-1999), 2000-2004, 2005-2009, 2010-2014 and 2015-2020.

To test the effect of treatment, tree size (DBH classes), time (period pre and post treatment) on the pre and post treatment BAI (response), we used a repeated measure analysis of variance with individual tree ID as repeated measures. Assumption for no significant outliers was checked through data visualization and Shapiro-Wilk normality test was conducted for checking the asssumptions for normality. During this analysis trees of <10 cm and >20 cm was omitted because of the low sample size (n=2 each). A significance level of α=0.05 was used for all the statistical analyses. To test the specific difference among the categorical variables a post hoc Tukey test was used.

3.3. Results

The pre-thinned (five-year average) Basal Area Increment (BAI) of thinned trees was slightly higher (mean= 332 mm^2) than the unthinned trees (mean=304 $mm^{2)}$ but was not significantly different (p=0.31). The BAI of the unthinned trees remained similar to pre-thinning

BAI throughout the post treatment periods with an average value of (316 mm^2, p=0.42). However, for thinned trees, the BAI increased by 128mm^2 immediately after thinning and continued to increase by 73 mm^2 up to 2005. After 2005 the growth increment in thinned trees plateaued. By 2015, the mean BAI for thinned tree was 529 mm^2 (Figure 9) .

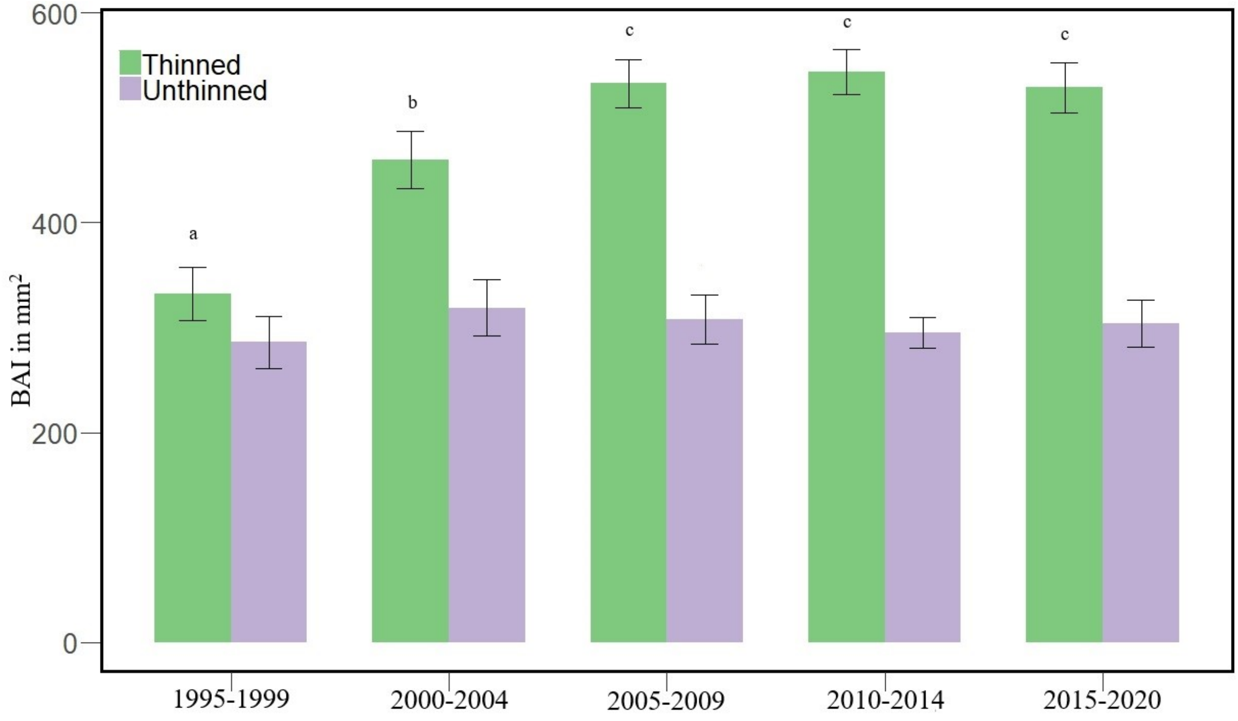


Figure 9. Basal Area Increment between thinned and unthinned trees at different time periods. The X-axis represents pre and post thinning time grouped into 5 years period and the Y-axis represents BAI in mm^2 per 5 years. The letter in the graph represents significant differences between thinned trees at different time periods.

Initial tree size at thinning is a significant predictor for the post thinning BAI in thinned trees (p<0.001, Figure 10). The post thinning BAI growth of thinned trees increased with increasing tree size, whereas it remained similar for the unthinned trees (Figure 10, S5). For individual size classes, the post thinning BAI was similar for trees within (10.1-12.5 cm, p=0.3).

The difference in them increased with the size class and was maximum for the largest size class trees (17.5-20 cm) by 246 mm^2 ($p<0.0001$).

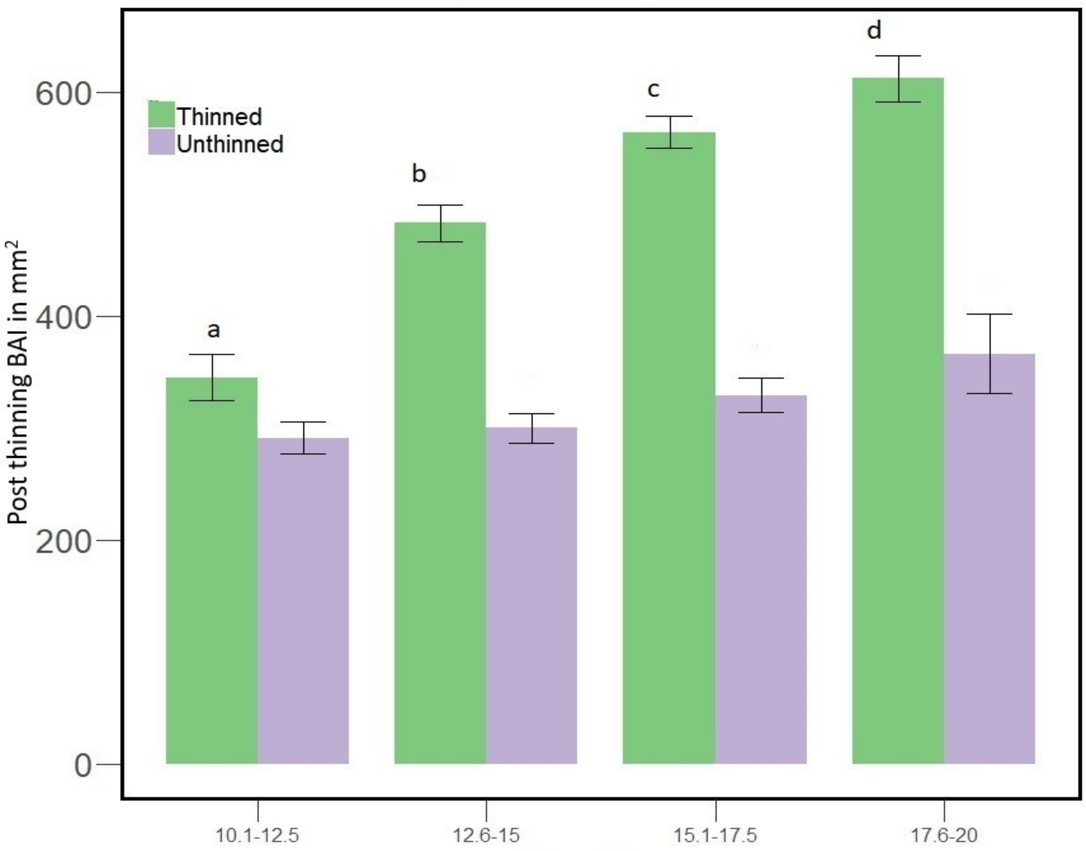


Figure 10. Twenty-year Basal Area Increment between thinned and unthinned trees of different sizes. The X-axis represents tree sizes group at an interval of 2.5 cm and the Y-axis represents the post thinning BAI in mm^2 average from 5 years. The letter in the graph represents significant differences between thinned trees at different time periods

Although, thinning increased the post thinning individual tree BAI, growth response shown by individual size classes was different for different time periods. For instance, the smallest size class (10.1-12.5 cm), had a delayed response and showed no growth increment during the first period (2000-2004). However, after 2005, growth increased at a slower pace. By 2020, smallest sized thinned trees have 1.5 times BAI than the unthinned trees. For medium sized trees within range (12.5-17.5 cm), growth response to thinning was immediate and these trees dominated the growth of unthinned trees by 1.6 times within the first period. By 2014, the growth in BAI of thinned trees was twice the unthinned trees. However, response declined after 15 years. Lastly, for trees the biggest trees, growth response post thinning was slower, gradually dominating the unthinned by 1.3 times in 2005 to 1.6 times in 2015. Despite the slow growth, these trees continue to grow even after 15 years (Figure 11).

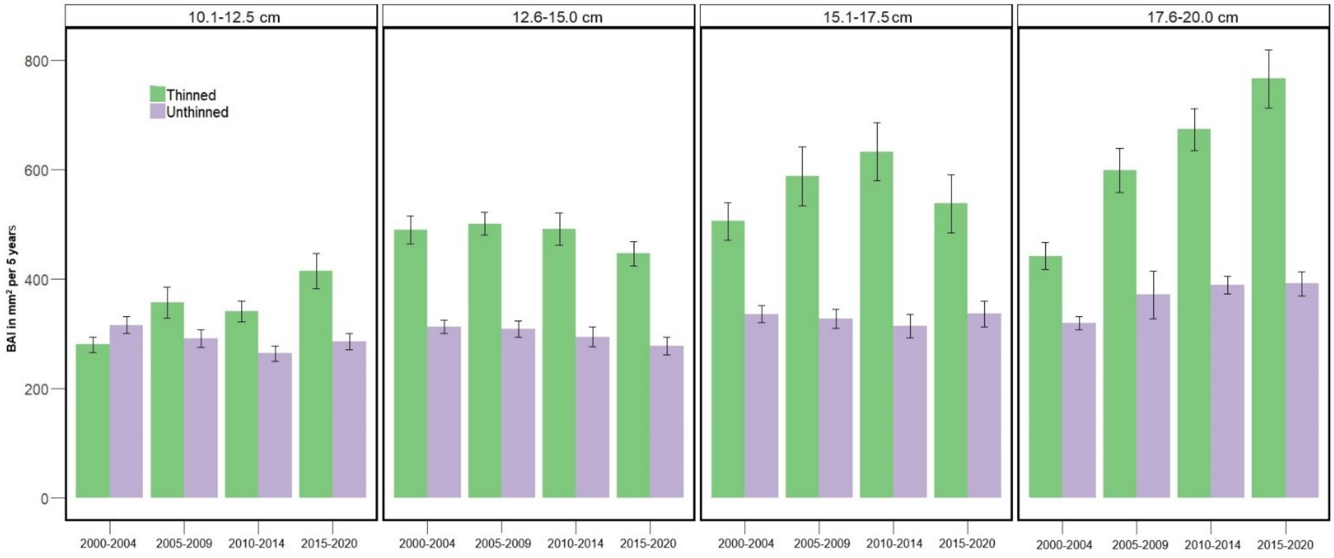


Figure 11. Twenty-year Basal Area Increment between thinned and unthinned trees of different sizes classes at different time periods. The X-axis represents tree sizes group at an interval of 2.5 cm and the Y-axis represents BAI in mm^2.

3.4. Discussion

Thinning increases the Basal Area Increment of individual trees, with the temporal growth effect of thinning lasting up to 15 years or even continuing after 20 years, depending upon individual tree size at thinning. For instance, smaller trees have delayed post thinning growth and is short lived, medium trees have immediate growth response lasting up to 15 years. In contrast, larger trees have a slower growth response, but the increment continues even after 15 years. Tree size at thinning also influence, magnitude of tree growth, which increases with increasing size of trees at thinning.

The objective of this commercial thinning for the study was to increase the growth of trees at 68-years (Dempster, 2001), and our findings show the objective was met, as BAI of thinned trees was greater than unthinned trees. This post thinning increment in BAI was due to increase in amount of carbohydrates produced by trees from growing space for root and crown expansion (Smithers, 1996). The post thinning BAI increased with the increasing size classes of trees but the growth for thinned was greater than unthinned trees. The reason for enhanced growth is thinned trees is due to increased amount of carbohydrate produced by trees from growing space for root and crown expansion (Smithers, 1996.). This relationship between the tree size and BAI growth is also reported in Scots pine (Peltola et al., 2007), black spruce (Tong et al., 2011), sugar maple, and yellow birch (Baral et al., 2016) irrespective of thinning intensity and site quality.

The temporal response to thinning was not immediate for the small class (10.1-12.5 cm) and the largest trees (17.6-20 cm). This delay in thinning response is attributed to a physiological phenomenon known as "thinning shock." Multiple factors can contribute to thinning shock in conifers (Donner and Running, 1986). The potential reason for the delayed response in small trees could be the abrupt exposure to high-light conditions. Since these trees were previously suppressed in the canopy, the sudden gap created by thinning can lead to damage in the photosystems, resulting in a temporary decrease in photosynthetic efficiency (Bannister et al., 2013; Masaka et al., 2013; Yang, 1998). The smaller trees also do not have enough leaf area to respond immediately to the thinning. Besides, the delayed response, growth of small trees was slower than other size classes due to competition for above and below-ground resources, which is mainly tapped by large and medium size trees after thinning (Baral et al., 2016; Das Gupta et al., 2020). The age-related growth declination could be other possible reason as these trees have been suppressed for a long period of time and were already older enough for the given diameter (i.e., 10.1-12.5 cm at the age of 68) (Baral et al., 2016; Ryan et al., 1997). If the objective of management is to increase the growth of these suppressed trees, then some commercial thinning studies recommended intensive thinning to 1000-1200 trees/ha or lesser (Tong et al., 2011).

In contrast to smaller trees, the larger trees (17.6-20 cm) were already dominant in the canopy, therefore light exposure was not the reason for the slow growth of these trees. Instead, larger trees might have undergone gradual acclimatization response due to the sudden change in micro-climate condition by thinning. This acclimatization process can involve resource allocation in the root instead on the truck of the trees and can last for a few years (e.g., 3- years in white pine) to over 15 years in white spruce (Urban et al., 1994). In this case, we assume the radial growth in root might have lasted for 9-10 years because the growth in DBH is slower until this period but increases after 2009. Beside growth acclimatization, increased transpiration after thinning, that cause water loss through sap flow in trees and delayed growth in trees (Lagergren et al., 2008; Rubilar et al., 2018). Although the larger trees show initial declines, growth continues in them even, at the age of 90.

The medium sized (12.5-17.5 cm) however, had an immediate response to thinning and the growth increment continued for 15 years. Similar growth trend has been reported by co-dominant trees on other thinning studies in sugar maple, yellow birch, white spruce. These trees were co-dominant in the canopy and light was likely the main growth limiting factors for them. Being shade intolerant, the canopy gap created by thinning increased the light and resources availability and ultimately the photosynthetic rates leading to increased growth (Das Gupta et al., 2020; Primicia et al., 2013). The growth of these sub-canopy trees continues until they extend their lateral crowns and closed the canopy, that studies indicated to be for around 15-20 years (Baral et al., 2016). The declining growth of small and medium trees after the initial peak could also be due to a) re-establishment of Leaf Area Index (LAI) to pre thinning and b) the increasing age of the trees. As the stand was 68 years old, so growth rate declines due to the decline in the rate of photosynthesis and shorter periods of the cambial activities (Bond et al., 1994; Vieira et al., 2009).

In Alberta, the impact of commercial thinning on the BAI of lodgepole pine trees during the late rotation stage (at 88 years of age) has not been previously investigated. Our study addressed this gap and found that commercial thinning conducted at age 68, to a stand density of 1680 trees per hectare, can increase the BAI of individual lodgepole pine trees. The magnitude of this growth response depends on the size of the tree at the time of thinning, with the most significant effects observed in trees within the 12.5-17.5 cm diameter classes. Notably, the increased BAI in thinned trees occurs gradually and remains sustained for a period of 10-15 years following the thinning operation.

Chapter IV: SUMMARY AND MANAGEMENT IMPLICATIONS

4.1. Summary of the studies

The findings of this research add input to our understanding on the effect of commercial thinning and nitrogen fertilization in late-rotation (88-year-old) natural lodgepole pine stands in Alberta. It also accesses the posthinning growth response, 20 years after thinning on trees of different size classes. The most important takeaway of the study is the increased cumulative merchantable volume (Figure 2). Commercial thinning along was able to increase cumulative merchantable volume by 6.3 m^3/ha. Although the stand basal area growth between the thinned and untinned was similar in 20 years, commercial thinning increased the stand value by increasing the proportion of saw log trees by 17.5% (Figure 4). The individual DBH growth in commercial thinned trees was 1.3 times the unthinned (Figure 5). Therefore, the key conclusion is commercial thinning alone can be a potential management option for natural-lodgepole pine at the later rotation. This means if the goal of forest practitioners in Alberta is to manage natural lodgepole pine stands, the commercial thinning with a 50% basal area reduction can be considered to enhance the growth of natural lodgepole pine forests.

Fertilization increased the growth of individual trees, with the highest growth benefit observed at 400 kg/ha levels of fertilization. The 400 kg/ha fertilization alone reduced the cumulative merchantable volume by 19.2 m^2/ha. Although there was an increase in individual tree DBH by 1.13 times, the decrease in merchantable volume was the due to the result of increased mortality by an average of 14.7%.

The maximum stand and individual tree level benefits were achieved when commercial thinning was combined with 400 kg/ha nitrogen. This combination increased the cumulative merchantable volume of the stand by 24.6 m^3/ha and the proportion of trees that make good saw log by 17.6%. Individual tree DBH increment was by 1.56 times. Therefore, the key takeaway is that for optimal benefits, fertilization should be complemented with thinning practices. (Figure *5*). For fertilization levels, 200 kg/ha N did not have significant growth increase in lodgepole pine, therefore future studies can plan 400 kg/ha N with either (urea or ammonia) as a source of nitrogen in the fertilizer. The summary of the findings of the commercial thinning and fertilization study is demonstrated in (Figure *12*).

The temporal response study found that commercial thinning increases the Basal Area Increment of tress of all size class, however, the intensity and duration of the response varied by size at thinning. For the smaller trees, of size (10.1-12.5 cm), growth was delayed for the first 5 years, however these trees able to respond followed by slow growth response. The medium size class with DBH ranging from (12.5-17.5 cm) showed an immediate response to thinning. Growth of these trees peaked until 14th year of thinning and then starts declining. The largest trees with size (17.5-20 cm) had slower but gradual growth post thinning, with continued growth even after 20 years (Figure 11). The key takes away finding from this temporal study is growth effect of thinning in lodgepole pine can last for 15 years or more depending upon the size class. Therefore, a second entry (commercial thinning) or harvesting may be planned after 15 years of thinning in late rotation lodgepole pine forests.

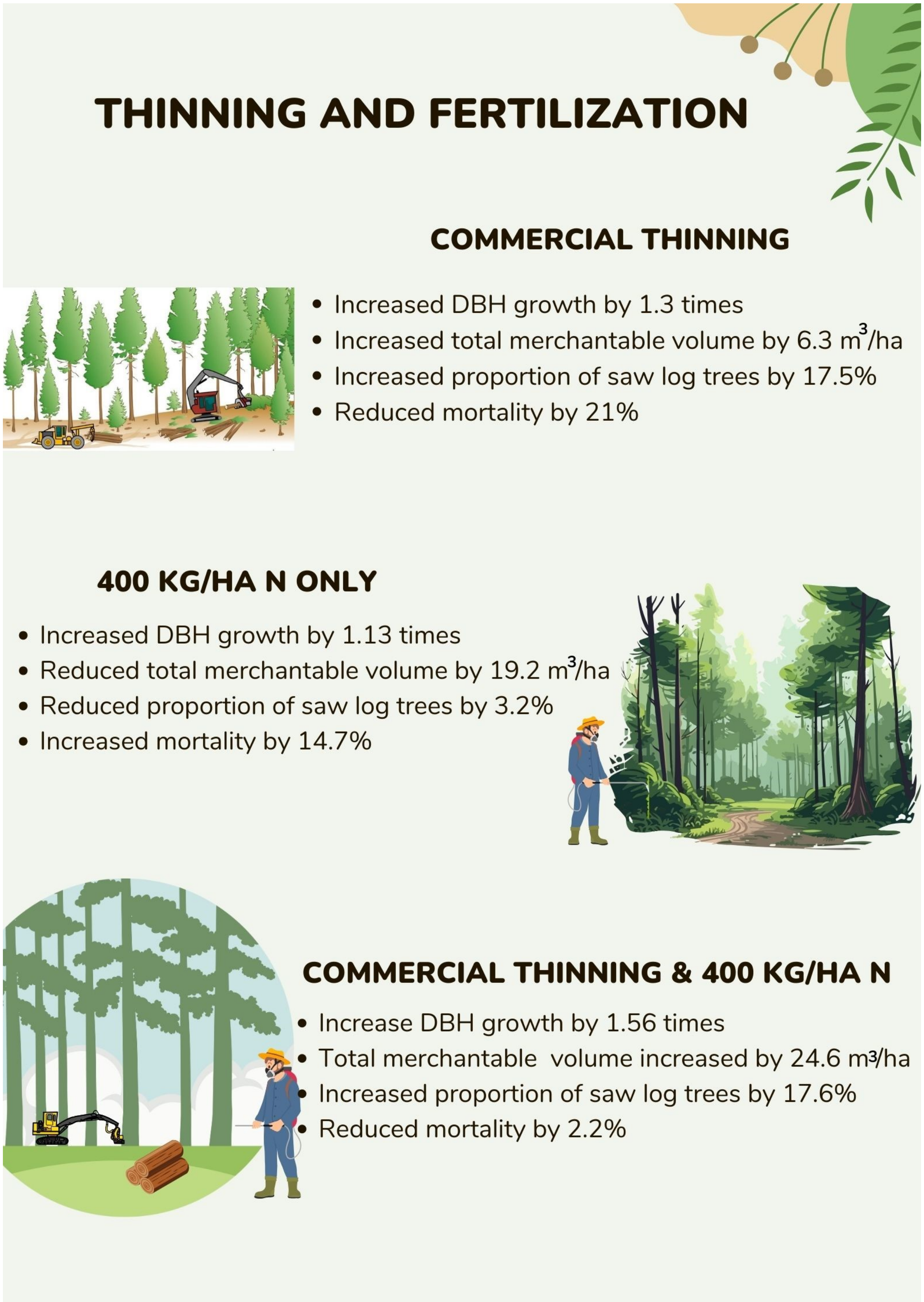
4.2. Limitations of the study

- The study is conducted at a single site; therefore, the recommendations made from this study can be applied to other sites with similar characteristics. Due to the limitation in landscape-level replications, the findings of the study cannot be extrapolated for operational management elsewhere.

- The temporal study has included the DBH at thinning and time period as a factor. Although the study uses repeated measures ANOVA to account the repeated measurement of individual tree data, the results might have differed if we had analyzed the study using the annual increment data. However, due to the limitation in time, we analyzed the study
- In addition to thinning, several factors can influence the temporal growth of the trees such as precipitation, drought, nutrient availability in the nearby sites etc. However, these factors were not within the scope of the study and have not been included in the model.

4.3. Future research recommendations

- The result of the study forms a baseline for the effect of commercial thinning and fertilization in a late rotation natural lodgepole pine stand. We recommend replication of similar studies at an operational scale on sites with different site quality, density, age and thinning intensity for deriving management implications for Alberta. A follow up study that accesses temporal growth response of individual trees at the different thinning and fertilization plots can be studied to access how fertilization alone and in combination of thinning influences temporal response.
- As there are limited studies in lodgepole pine that looks at the temporal growth response, we recommend future studies to account the climate and thinning data to make a better post treatment growth of individual trees.



THINNING AND FERTILIZATION

COMMERCIAL THINNING

- Increased DBH growth by 1.3 times
- Increased total merchantable volume by 6.3 m^3/ha
- Increased proportion of saw log trees by 17.5%
- Reduced mortality by 21%

400 KG/HA N ONLY

- Increased DBH growth by 1.13 times
- Reduced total merchantable volume by 19.2 m^3/ha
- Reduced proportion of saw log trees by 3.2%
- Increased mortality by 14.7%

COMMERCIAL THINNING & 400 KG/HA N

- Increase DBH growth by 1.56 times
- Total merchantable volume increased by 24.6 m^3/ha
- Increased proportion of saw log trees by 17.6%
- Reduced mortality by 2.2%

Figure 12. Key take away message of the thinning and fertilization study

References

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments, in: Forest Ecology and Management. pp. 83–96. https://doi.org/10.1016/j.foreco.2005.01.034

Alberta's Forest Economy, 2021. A Handbook of Public Economic and Socioeconomic Accounts.

Alberta Environment., 2006. Natural regions and subregions of Alberta : Natural Regions Committee. Government of Alberta.

Aldea, J., Bravo, F., Bravo-Oviedo, A., Ruiz-Peinado, R., Rodríguez, F., del Río, M., 2017. Thinning enhances the species-specific radial increment response to drought in Mediterranean pine-oak stands. Agric. For. Meteorol. 237–238, 371–383. https://doi.org/10.1016/j.agrformet.2017.02.009

Ara, M., Pinno, B.D., Scaria, F., Froese, R.E., Bokalo, M., 2023. Thinning Increases Individual Tree Growth While Reducing the Growth Heterogeneity of Lodgepole Pine. Forests 14, 1091. https://doi.org/10.3390/f14061091

Bannister, J.R., Coopman, R.E., Donoso, P.J., Bauhus, J., 2013. The importance of microtopography and nurse canopy for successful restoration planting of the slow-growing conifer Pilgerodendron uviferum. Forests 4, 85–103. https://doi.org/10.3390/f4010085

Baral, S.K., Danyagri, G., Girouard, M., Hébert, F., Pelletier, G., 2016. Effects of suppression history on growth response and stem quality of extant northern hardwoods following partial harvests. For. Ecol. Manage. 372, 236–246. https://doi.org/10.1016/j.foreco.2016.04.023

Bergh, J., Nilsson, U., Allen, H.L., Johansson, U., Fahlvik, N., 2014. Long-term responses of Scots pine and Norway spruce stands in Sweden to repeated fertilization and thinning. For. Ecol. Manage. 320, 118–128. https://doi.org/10.1016/j.foreco.2014.02.016

Blevins, D.P., Prescott, C.E., Allen, H.L., Newsome, T.A., 2005. The effects of nutrition and density on growth, foliage biomass, and growth efficiency of high-density fire-origin lodgepole pine in central British Columbia. Can. J. For. Res. 35, 2851–2859. https://doi.org/10.1139/x05-204

Boivin-Dompierre, S., Achim, A., Pothier, D., 2017. Functional response of coniferous trees and stands to commercial thinning in eastern Canada. For. Ecol. Manage. 384. https://doi.org/10.1016/j.foreco.2016.10.024

Bond, B.J., Ryan, M.G., Waring, R.H., Schoettle, A.W., 1994. Evidence of Reduced Photosynthetic Rates in Old Trees. For. Sci. 40, 513–527.

Bose, A.K., Harvey, B.D., Brais, S., Beaudet, M., Leduc, A., 2014. Constraints to partial

cutting in the boreal forest of Canada in the context of natural disturbance-based management: A review. Forestry 87, 11–28. https://doi.org/10.1093/forestry/cpt047

Bose, A.K., Weiskittel, A., Kuehne, C., Wagner, R.G., Turnblom, E., Burkhart, H.E., 2018a. Does commercial thinning improve stand-level growth of the three most commercially important softwood forest types in North America? For. Ecol. Manage. 409, 683–693. https://doi.org/10.1016/j.foreco.2017.12.008

Bose, A.K., Weiskittel, A., Kuehne, C., Wagner, R.G., Turnblom, E., Burkhart, H.E., 2018b. Tree-level growth and survival following commercial thinning of four major softwood species in North America. For. Ecol. Manage. 427, 355–364. https://doi.org/10.1016/j.foreco.2018.06.019

Boucher, D., Boulanger, Y., Aubin, I., Bernier, P.Y., Beaudoin, A., Guindon, L., Gauthier, S., Beaudoin, A.E., 2018. Current and projected cumulative impacts of fire, drought, and insects on timber volumes across Canada 28, 1245–1259. https://doi.org/10.2307/26623225

Brecka, A.F.J., Shahi, C., Chen, H.Y.H., 2018. Climate change impacts on boreal forest timber supply. For. Policy Econ. https://doi.org/10.1016/j.forpol.2018.03.010

Brockley, R.P., 2005. Effects of post-thinning density and repeated fertilization on the growth and development of young lodgepole pine. Can. J. For. Res. 35, 1952–1964. https://doi.org/10.1139/x05-124

Brockley, R.P., 2001. Fertilization of lodgepole pine in western Canada, in: Proceedings of Enhanced Forest Management: Fertilization & Economics. pp. 1–12.

Brockley, R.P., 2000. Using foliar variables to predict the response of lodgepole pine to nitrogen and sulphur fertilization. Can. J. For. Res. 30. https://doi.org/10.1139/x00-066

Brockley, R.P., 1995. Effect of nitrogen source and season of application on the nutrition and growth of lodgepole pine. Can. J. For. Res. 25, 516–526.

Brockley, R.P., 1990. Response of thinned, immature lodgepole pine to nitrogen and boron fertilization. Can. J. For. Res. 20. https://doi.org/10.1139/x90-075

Carter, R.E., Brockley, R.P., 1990. Boron deficiencies in British Columbia: Diagnosis and treatment evaluation, Forest Ecology and Management.

Chen, C., Nelson, A.S., Shaw, T., Kimsey, M., 2022. Effects of fertilization on the growth dominance of Inland Northwest forests of the United States. For. Ecosyst. 9. https://doi.org/10.1016/j.fecs.2022.100038

Cochran, P.H., Dahms, W.G., 1998. Lodgepole Pine Development After Early Spacing in the Blue Mountains of Oregon.

Cook, S.P., Carroll, A.D., Kimsey, M., Shaw, T.M., 2015. Changes in a primary resistance parameter of lodgepole pine to bark beetle attack one year following fertilization and thinning. Forests 6. https://doi.org/10.3390/f6020280

CooRecorder, C.D. and, n.d. C. Dendro and CooRecorder [WWW Document]. URL https://cdendro.se/dendro/dendro-tools/

Das Gupta, S., Pinno, B.D., McCready, T., 2020. Commercial thinning effects on growth, yield and mortality in natural lodgepole pine stands in Alberta. For. Chron. 96. https://doi.org/10.5558/tfc2020-016

Dempster, R., 2001. Factorial Thinning and Fertilizer Research Trial in Stand 5 McLeod 18 Compartment. Welwood Canada,hint. Div.

Dempster, W.R., Meredith, S., 2014. A discussion of best management practices for reforestation following harvesting of lodgepole pine in the Alberta Foothills. For. Chron. 90, 763–770. https://doi.org/10.5558/tfc2014148

Donner, B.L., Running, S.W., 1986. Water Stress Response After Thinning Pinus contorts Stands in Montana. For. Sci. 32, 614–625.

Farnden, C., Herring, L., 2002. Severely repressed lodgepole pine responds to thinning and fertilization: 19-year results. For. Chron. 78.

FGROW, 2022. Forestry Toolbox [WWW Document]. URL https://fgrow.ca/fri-subject-area/forest-management (accessed 1.3.22).

Fox, T.R., Allen, H.L., Albaugh, T.J., Rubilar, R., Carlson, C.A., 2007. Tree nutrition and forest fertilization of pine plantations in the southern United States. South. J. Appl. For. 31, 5–11. https://doi.org/10.1093/sjaf/31.1.5

Garrison, M.T., Moore, J.A., Shaw, T.M., Mika, P.G., 2000. Foliar nutrient and tree growth response of mixed-conifer stands to three fertilization treatments in northeast Oregon and north central Washington. For. Ecol. Manage. 132. https://doi.org/10.1016/S0378-1127(99)00228-5

Gauthier, M.M., Barrette, M., Tremblay, S., 2015. Commercial thinning to meet wood production objectives and develop structural heterogeneity: A case study in the spruce-fir forest, Quebec, Canada. Forests 6, 510–532. https://doi.org/10.3390/f6020510

Gauthier, M.M., Tremblay, S., 2019. Late-entry commercial thinning effects on Pinus banksiana: growth, yield, and stand dynamics in Québec, Canada. J. For. Res. 30. https://doi.org/10.1007/s11676-018-0778-3

Girona, M.M., Morin, H., Lussier, J.M., Walsh, D., 2016. Radial growth response of black spruce stands ten years after experimental shelterwoods and seed-tree cuttings in boreal forest. Forests 7. https://doi.org/10.3390/f7100240

Girona, M.M., Rossi, S., Lussier, J.M., Walsh, D., Morin, H., 2017. Understanding tree growth responses after partial cuttings: A new approach. PLoS One 12. https://doi.org/10.1371/journal.pone.0172653

Government of Alberta, 2012. Alberta's Forest Products Buyer's Guide.

Griess, V.C., Man, C.D., Polinko, A.D., Spies, J., 2019. Mitigating midterm timber supply shortage using commercial thinning operations. A case study from British Columbia, Canada. For. Ecol. Manage. 443, 1–18. https://doi.org/10.1016/j.foreco.2019.04.003

Hossain, K.L., Lieffers, V.J., Pinn, B.D., 2022. Thinning to meet sawlog objectives at shorter rotation in lodgepole pine stands. Can. J. For. Res. 52, 940–950. https://doi.org/10.1139/cjfr-2022-0006

Huang, S., 1994. Ecologically based individual tree volume tables for lodgepole pine.

Huuskonen, S., Hynynen, J., 2006. Timing and intensity of precommercial thinning and their effects on the first commercial thinning in Scots pine stands. Silva Fenn. 40, 645–662. https://doi.org/10.14214/sf.320

Johnstone, W.D., 2002. Thinning Lodgepole Pine in Southeastern British Columbia: 46-year Results (No. 63).

Jones, A., 2014. 2014 Detailed Forest Management Plan.

Jones, T.A., Domke, G.M., Thomas, S.C., 2009. Canopy tree growth responses following selection harvest in seven species varying in shade tolerance. Can. J. For. Res. 39, 430–440. https://doi.org/10.1139/X08-186

Keane, M., Weetman, G., 1987. Leaf area-sapwood cross-sectional area relationships in repressed stands of lodgepole pine. Can. J. For. Res. 17. https://doi.org/https://doi.org/10.1139/x87-036

Kishchuk, B.E., Weetman, G.F., Brockley, R.P., Prescott, C.E., 2002a. Fourteen-year growth response of young lodgepole pine to repeated fertilization. Can. J. For. Res. 32. https://doi.org/10.1139/x01-181

Kishchuk, B.E., Weetman, G.F., Brockley, R.P., Prescott, C.E., 2002b. Fourteen-year growth response of young lodgepole pine to repeated fertilization. Can. J. For. Res. 32, 153–160. https://doi.org/10.1139/x01-181

Kuehne, C., Weiskittel, A., Pommerening, A., Wagner, R.G., 2018. Evaluation of 10-year temporal and spatial variability in structure and growth across contrasting commercial thinning treatments in spruce-fir forests of northern Maine, USA. Ann. For. Sci. 75. https://doi.org/10.1007/s13595-018-0697-7

Lagergren, F., Lankreijer, H., Kučera, J., Cienciala, E., Mölder, M., Lindroth, A., 2008. Thinning effects on pine-spruce forest transpiration in central Sweden. For. Ecol. Manage. 255, 2312–2323. https://doi.org/10.1016/j.foreco.2007.12.047

Lieffers, V.J., Pinno, B.D., Beverly, J.L., Thomas, B.R., Nock, C., 2020. Reforestation policy has constrained options for managing risks on public forests. Can. J. For. Res. 50, 855–861. https://doi.org/10.1139/cjfr-2019-0422

Linares, J.C., Tíscar, P.A., 2010. Climate change impacts and vulnerability of the southern populations of Pinus nigra subsp. salzmannii. Tree Physiol. 30, 795–806.

https://doi.org/10.1093/treephys/tpq052

Lockwood, B.R., Maxwell, J.T., Robeson, S.M., Au, T.F., 2021. Assessing bias in diameter at breast height estimated from tree rings and its effects on basal area increment and biomass. Dendrochronologia 67. https://doi.org/10.1016/j.dendro.2021.125844

Manrique-Alba, À., Beguería, S., Tomas-Burguera, M., Camarero, J.J., 2021. Increased post-drought growth after thinning in pinus nigra plantations. Forests 12. https://doi.org/10.3390/f12080985

Masaka, K., Sato, H., Torita, H., Kon, H., Fukuchi, M., 2013. Thinning effect on height and radial growth of Pinus thunbergii Parlat. trees with special reference to trunk slenderness in a matured coastal forest in Hokkaido, Japan. J. For. Res. 18, 475–481. https://doi.org/10.1007/s10310-012-0373-y

Mehtatalo, L., Peltola, H., Kilpelainen, A., Ikonen, V.P., 2014. The response of basal area growth of scots pine to thinning: A longitudinal analysis of tree- specific series using a nonlinear mixed-effects model. For. Sci. 60, 636–644. https://doi.org/10.5849/forsci.13-059

Mitchell, R.G., Waring, R.H., Pitman, G.B., 1983. Thinning Lodgepole Pine Increases Tree Vigor and Resistance to Mountain Pine Beetle, Forest ScL.

Moulinier, J., Brais, S., Harvey, B.D., Koubaa, A., 2015a. Response of boreal jack pine (Pinus banksiana lamb.) Stands to a gradient of commercial thinning intensities, with and without N fertilization. Forests 6. https://doi.org/10.3390/f6082678

Moulinier, J., Brais, S., Harvey, B.D., Koubaa, A., 2015b. Response of boreal jack pine (Pinus banksiana lamb.) Stands to a gradient of commercial thinning intensities, with and without N fertilization. Forests 6, 2678–2702. https://doi.org/10.3390/f6082678

Natural Resources Canada, 2021. The State of Canada's Forests Annual Report 2021.

Navratil, S., Northern Forestry Centre (Canada), Weldwood (Firm), 2002. A lodgepole pine commmercial thinning trial in Kananaskis, Alberta : 58-year results. Northern Forestry Centre.

Peet, R.K., Christensen, N.L., 1987. Competition and Tree Death. Bioscience 37, 586–595. https://doi.org/10.2307/1310669

Pelletier, G., Pitt, D.G., 2008. Silvicultural responses of two spruce plantations to midrotation commercial thinning in New Brunswick. Can. J. For. Res. 38, 851–867. https://doi.org/10.1139/X07-173

Peltola, H., Kilpeläinen, A., Sauvala, K., Räisänen, T., Ikonen, V.-P., 2007. Effects of Early Thinning Regime and Tree Status on the Radial Growth and Wood Density of Scots Pine. Silva Fenn. 41, 489–505.

Pinno, B.D., Hossain, K.L., Gooding, T., Lieffers, V.J., 2021a. Opportunities and challenges for intensive silviculture in alberta, canada. Forests 12.

https://doi.org/10.3390/f12060791

Pinno, B.D., Lieffers, V.J., Landhäusser, S.M., 2012. Inconsistent Growth Response to Fertilization and Thinning of Lodgepole Pine in the Rocky Mountain Foothills Is Linked to Site Index. Int. J. For. Res. 2012. https://doi.org/10.1155/2012/193975

Pinno, B.D., Thomas, B.R., Lieffers, V.J., 2021b. Wood supply challenges in Alberta – Growing more timber is the only sustainable solution. For. Chron. 97, 106–108. https://doi.org/10.5558/tfc2021-013

Plauborg, K.U., 2004. Analysis of radial growth responses to changes in stand density for four tree species. For. Ecol. Manage. 188, 65–75. https://doi.org/10.1016/j.foreco.2003.07.022

Prescott, C., Demontigny, L., Harper, G., 2019. Eighteen-year growth responses to thinning and fertilization of a height-repressed lodgepole pine stand in interior British Columbia. For. Chron. 95.

Price, D.T., Alfaro, R.I., Brown, K.J., Flannigan, M.D., Fleming, R.A., Hogg, E.H., Girardin, M.P., Lakusta, T., Johnston, M., McKenney, D.W., Pedlar, J.H., Stratton, T., Sturrock, R.N., Thompson, I.D., Trofymow, J.A., Venier, L.A., 2013. Anticipating the consequences of climate change for Canada's boreal forest ecosystems1. Environ. Rev. https://doi.org/10.1139/er-2013-0042

Primicia, I., Camarero, J.J., Imbert, J.B., Castillo, F.J., 2013. Effects of thinning and canopy type on growth dynamics of Pinus sylvestris: Inter-annual variations and intra-annual interactions with microclimate. Eur. J. For. Res. 132, 121–135. https://doi.org/10.1007/s10342-012-0662-1

Reid, A., Montigny, L. de, Prescott, C., Sajedi, T., 2017. A systematic review of forest fertilization research in interior British Columbia. Tree Species Effects on Nitrogen cycling and soil microbial communities View project MASS-Montane Alternative Silvicultural Systems View project.

Rowan, M., 2012. Mitigating the Mid-term Timber Supply Gap: Potential Silvicultural Solutions in the Prince George TSA Mitigating the Mid-term Timber Supply Gap.

Rubilar, R.A., Lee Allen, H., Fox, T.R., Cook, R.L., Albaugh, T.J., Campoe, O.C., 2018. Advances in Silviculture of Intensively Managed Plantations. Curr. For. Reports. https://doi.org/10.1007/s40725-018-0072-9

Scaria, F., 2023. Pre-Commercial Thinning Increases Merchantability and Reduces Western Gall Rust Infections in Lodgepole Pine. University of Alberta.

Senko, S., Kurttila, M., Karjalainent, T., 2018. Prospects for Nordic intensive forest management solutions in the Republic of Karelia. Silva Fenn. 52. https://doi.org/10.14214/sf.7763

Sohn, J.A., Saha, S., Bauhus, J., 2016. Potential of forest thinning to mitigate drought stress: A meta-analysis. For. Ecol. Manage. 380, 261–273.

https://doi.org/10.1016/j.foreco.2016.07.046

Soucy, M., Lussier, J.M., Lavoie, L., 2012. Long-term effects of thinning on growth and yield of an upland black spruce stand. Can. J. For. Res. 42, 1669–1677. https://doi.org/10.1139/X2012-107

Stanturf, J.A., Kellison, R.C., Broerman, F.S., Jones, S.B., 2003. Innovation and forest industry: Domesticating the pine forests of the southern United States, 1920-1999, in: Forest Policy and Economics. Elsevier, pp. 407–419. https://doi.org/10.1016/S1389-9341(03)00039-X

Sullivan, T.P., Sullivan, D.S., 2017a. Old-growth characteristics 20 years after thinning and repeated fertilization of lodgepole pine forest: Tree growth, structural attributes, and red-backed voles. For. Ecol. Manage. 391. https://doi.org/10.1016/j.foreco.2017.02.021

Sullivan, T.P., Sullivan, D.S., 2017b. Old-growth characteristics 20 years after thinning and repeated fertilization of lodgepole pine forest: Tree growth, structural attributes, and red-backed voles. For. Ecol. Manage. 391, 207–220. https://doi.org/10.1016/j.foreco.2017.02.021

Sullivan, T.P., Sullivan, D.S., 2016. Acceleration of old-growth structural attributes in lodgepole pine forest: Tree growth and stand structure 25 years after thinning. For. Ecol. Manage. 365, 96–106. https://doi.org/10.1016/j.foreco.2016.01.029

Sullivan, T.P., Sullivan, D.S., Lindgren, P.M.F., Ransome, D.B., Zabek, L., 2020a. Twenty-five years after stand thinning and repeated fertilization in lodgepole pine forest: Implications for tree growth, stand structure, and carbon sequestration. Forests 11. https://doi.org/10.3390/f11030337

Sullivan, T.P., Sullivan, D.S., Lindgren, P.M.F., Ransome, D.B., Zabek, L., 2020b. Twenty-five years after stand thinning and repeated fertilization in lodgepole pine forest: Implications for tree growth, stand structure, and carbon sequestration. Forests 11. https://doi.org/10.3390/f11030337

Swetnam, A., Ares, M., Kennedy, E., 1985. Using Dendrochronology To Measure Radial Growth of Defoliated Trees Item Type Book.

Tong, Q., Tanguay, F., Zhang, S.Y., 2011. Impact of commercial thinning on annual radial growth and wood density in plantation-grown black spruce. Wood Fiber Sci. 43, 311–325.

Urban, S.T., Lieffers, V.J., MacDonald, S.E., 1994. Release in radial growth in the trunk and structural roots of white spruce as measured by dendrochronology. Can. J. For. Res. 24, 1550–1556.

Valinger, E., Èrn Elfving, B., Mo Èrling, T., 2000. Twelve-year growth response of Scots pine to thinning and nitrogen fertilisation 45–53.

Valinger, E., Sjögren, H., Nord, G., Cedergren, J., 2019. Effects on stem growth of Scots pine 33 years after thinning and/or fertilization in northern Sweden. Scand. J. For.

Res. 34, 33–38. https://doi.org/10.1080/02827581.2018.1545920

Vieira, J., Campelo, F., Nabais, C., 2009. Age-dependent responses of tree-ring growth and intra-annual density fluctuations of Pinus pinaster to Mediterranean climate. Trees - Struct. Funct. 23, 257–265. https://doi.org/10.1007/s00468-008-0273-0

Ward, C., Erdle, T., 2015. Evaluation of forest management startegies based on Triad zoning. For. Chron. 91, 40–51.

Weetman, G.F., 1988. Nutrition and fertilization of lodgepole pine. Gen. Tech. Rep. - US Dep. Agric. For. Serv.

Whitehead, R.J., Russo, G.L., Hawkes, B.C., Armitage, O.B., 2007. A silvicultural assessment of 10 lodgepole pine stands after partial cutting to reduce susceptibility to mountain pine beetle, Natural Resources Canada.

Yang, R.C., 1998. Foliage and stand growth responses of semimature lodgepole pine to thinning and fertilization.

Yang, R.C., 1985. Ten-year growth response of 70-year-old lodgepole pine to fertilization in Alberta. Northern Forest Research Centre.

Yang, R.C., Wang, E.I.C., Micko, M.M., 1988. Effects of fertilization on wood density and tracheid length of 70-year-old lodgepole pine in west-central Alberta. Can. J. For. Res. 18. https://doi.org/10.1139/x88-145

Zhao, D., Bullock, B.P., Montes, C.R., Wang, M., 2022. Production, tree size inequality and growth dominance in loblolly pine plantations under different silvicultural management regimes. For. Ecol. Manage. 526. https://doi.org/10.1016/j.foreco.2022.120594

Zhu, Z., Kleinn, C., Nölke, N., 2021. Assessing tree crown volume - A review. Forestry. https://doi.org/10.1093/forestry/cpaa037

Appendix

Table A1. ANOVA Table for standing merchantable volume

	df	F value	P value
Thinning	1	4.36	0.04
Fertilization	5	24.5	<0.01
Thinning*Fertilization	5	17.39	<0.001

Table A2. Standing merchantable volume according to fertilization levels.

Fertilization	merchantable volume (m3/ha)
No fertilizer	193.6
200 kg/ha N+Boron	192.2
200 kg/ha N+blend	176.5
400 kg/ha N+ Boron	149.2
400 kg/ha N+ blend	170.5
400 kg/ha Ammonium nitrate +Boron	204.2

Table A3. Summary table for proportion of saw log trees

Thinning	Fertilization	Proportion (%)
Commercial Thinning	No fertilizer	39.7
Commercial Thinning	200 kg/ha N+Boron	46.2
Commercial Thinning	200 kg/ha N+blend	46.7
Commercial Thinning	400 kg/ha N+ Boron	59.9
Commercial Thinning	400 kg/ha N+ blend	52.9
Commercial Thinning	400 kg/ha Ammonium nitrate +Boron	40.7
Unthinned	No fertilizer	53.35
Unthinned	200 kg/ha N+Boron	61.19
Unthinned	200 kg/ha N+blend	60.63
Unthinned	400 kg/ha N+ Boron	65.85
Unthinned	400 kg/ha N+ blend	69.58
Unthinned	400 kg/ha Ammonium nitrate +Boron	68.23

Table A4. Summary table for the model of individual tree DBH growth.

Model=lmer(DBHGrowth~DBH+Thinning*Fertilization+(1|Block:Thinning)

	df (numerator, denominator)	F value	P value
DBH	1,1431	178.87	<0.001
Thinning	1,4	7.12	0.05
Fertilization	5,11	11.29	<0.002
Thinning*Fertilization	5,6	6.48	<0.001

Table A5. Anova table for the relationship between treatment and period

	df	F value	P value
Treatment	1 (1289.2)	34.7	<0.001
Period	5(1347.8)	49.506	<0.001
Treatment*Period	5(1347.8)	14.906	<0.001

Table A6. Anova table for the relationship between treatment and size

	df	F value	P value
Treatment	1 (829)	170.7	<0.001
Size	5(829)	29.35	<0.001
Treatment*Size	5(829)	12.40	<0.001