Pre-Commercial Thinning Increases Merchantability and Reduces Western Gall Rust Infections in Lodgepole Pine

by

Francis Scaria

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Abstract

Alberta's forest industry is predicted to be impacted by a short to medium-term decline in timber supply. Intensive silviculture tools, such as pre-commercial thinning, have been shown to increase individual tree growth, shorten rotation lengths and improve stand merchantability in important commercial species such as lodgepole pine. However, lodgepole pine stands are susceptible to western gall rust infections and thinning at an early stage may increase infection rates. But again, concrete information on these issues are missing from an operational scale. This study collected tree and stand level data from 33 operational harvest origin lodgepole pine stands consisting of 11 earlier thinned (PCT_18; 17-19 years), 11 later thinned (PCT_24; 23-25 years) and 11 unthinned stands. Pre-commercially thinned stands, regardless of timing, had greater individual tree size (~15% higher) compared to unthinned stands approximately 40 years after thinning. Pre-commercially thinned stands also have a higher potential for commercial thinning since they have lower variability in tree size and longer live crown lengths. In addition, the timing of thinning did have an impact on western gall rust infections, with PCT_24 stands having lower infection rates and infection severity compared to both PCT_18 and unthinned. In conclusion, pre-commercial thinning should be considered for lodgepole pine stands in order to address timber supply issues in Alberta.

Preface

The following thesis is composed of original data obtained and analyzed by Francis Scaria. The author was responsible for research design, data collection, data analysis, and manuscript composition. Dr. Bradley D. Pinno was involved with research design, data analysis, and manuscript edits. Sharon Meredith contributed to research design.

Results of this thesis "Effects of stand age at pre-commercial thinning on merchantability and western gall rust infections in lodgepole pine" were presented in a poster at the 89th Forest Industry Lecture Series Program from the University of Alberta. No part of this thesis has been previously published.

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CHAPTER 1: GENERAL INTRODUCTION

The forest industry is an important contributor to Alberta's economy accounting for around 1% of Alberta's GDP and by providing job opportunities to many communities in the province. The forest industry is a major employer in many municipalities throughout Alberta, accounting for approximately 27 percent of total employment income in the most forestry-dependent community (Alberta Forest Economy 2021). However, the short to medium-term timber supply is expected to decline in the province (Schneider et al. 2010; Das Gupta et al. 2020) as a consequence of the cumulative effect of unexpected events such as insect pest attacks, wildfires, etc. (Perez-Garcia et al. 2002; Lusebrink et al. 2013; Shegelski et al. 2021). The intensity and aggressiveness of forest pathogens may be amplified as they infect and harm stressed host trees, however it may also improve host resistance in some circumstances. The western boreal region is predicted to get warmer and drier, hence the pathogen activity and impact are probably going to increase (Johnston et al. 2010; Price et al. 2011; Price et al. 2013). Despite this situation, Government of Alberta intends to increase the timber harvesting and AAC on public lands by up to 13 % to promote the forest industry's viability (Government of Alberta 2020).

One potential solution to this timber supply issue is to use more intensive silviculture practices, such as pre-commercial thinning (PCT), on important commercial conifer species like lodgepole pine (Pinno et al. 2021). Intensive silviculture plays a significant role in: (1) shortening individual stand rotation lengths, (2) securing the supply of timber in the face of threat from insects, fire, and diseases (Lieffers et al. 2020) and (3) maintaining the sustainability of forestry industry that creates jobs and contribute towards GDP. Moreover, a forest industry that actively manages the land can build adaptation strategies for issues such as climate change and other forest risks (Lieffers et al.

2020; Park and Wilson 2007). With the interior plain's deep and rich soils with high water holding capacity and nutrient availability, Alberta is well suited for implementing intensive silviculture (Pinno et al. 2021). Although Alberta's public lands are its main source of industrial wood, these intense silvicultural practices are not commonly practiced (Pinno et al. 2021).

Pre-commercial thinning (PCT) is an important intensive silviculture tool that is used to reduce competition in young stands and level out the spacing between residual trees (Daniel et al. 1979). PCT involves removal of poor quality noncommercial size tress in an effort to reduce competition and improve growth in the residual trees by the redistribution of available growing space and resources (O'Hara 1989; Smith et al. 1997). PCT often promotes the diameter growth of individual trees (Pettersson 1993; Huuskonen and Hynynen 2006; Pitt and Lanteigne 2008) and gives the option to choose the desired future tree species composition (Fahlvik et al. 2011, Fahlvik et al. 2015). Improved light, moisture, and nutrients after PCT will reduce a range of resource barriers, alleviate numerous stresses on trees, and promote growth (Chase et al. 2016). Thinning enhances diameter and height growth (Prescott et al. 2019), which in turn results in greater volume. Besides, reducing the number of trees aids in the crown expansion of dominant trees, facilitating their growth (Johnstone 2002; Reid 2003; Reid 2004; Ferguson et al. 2011), which results in greater volume from bigger trees. In the residual trees, the size and persistence of crown are directly affected by available growing space (Johnstone and van Thienen 2004; Brockley 2011). A 20% increase in live crown has been observed in thinned lodgepole pine stands compared to unthinned stands at age 20 (Johnstone 2005). Additionally, removal of smaller and poor trees (Ferguson et al. 2011) and enhanced radial growth of remaining trees after thinning results in greater average tree size in thinned stands. Furthermore, shift in diameter distribution is likely in thinned stands from the impact of removal of smaller and poor trees (Hynynen 1995; Nogueira et al. 2015).

Lodgepole pine (*Pinus contorta. var. latifolia*.) is found throughout western North America, growing between 30 and 64 ° N latitudes and 0-3900 m elevation (Wheeler and Critchfield 1985). Throughout western North America, the species covers more than 5 million hectares in the United States and 20 million hectares in Canada (McDougal 1975; Wellner 1975). Its relative shade intolerance and slower growth rate in old stands will often allow secondary species to replace it in natural succession. The replacement age can vary greatly, and in poor sites, the species can remain dominant and form the final climax stage under certain conditions (Pfister and Daubenmire 1975).

Lodgepole pine is one of the most important commercial conifer tree species in Alberta (Government of Alberta 2012). In Alberta, more than 41% (over 600 million cubic meters) of the provincial coniferous growing stock (26 % of the total growing stock in the province) is comprised of pine (Alberta Forest economy 2021). Lodgepole pine is well recognized for its adaptation to frequent fire regimes through production of serotinous cones. The cones can store viable seeds for decades until they open in the heat of a fire or by exposure on the ground through felling (Lotan and Perry 1983). After wildfires and logging, lodgepole pine often regenerates in excessively dense stands. Such high densities decrease average stand height, diameter and merchantable volume but increase loss from mortality, length of rotations, and harvesting costs (Cole 1975; Johnstone 1985; Johnstone and Cole 1988; Johnstone 2005; Johnstone and van Thienen 2011). Density management through intensive silviculture practices such PCT is necessary in order to address the problems from high density and to provide a control over stand growth and yield. In addition, numerous advantages such as greater tolerance to abiotic stresses like drought, frost, and a lack of soil nutrients (Burns and Honkala 1990) make the species a good candidate for intensive silviculture. A number of the detrimental consequences of excessive density in lodgepole pine stands have been demonstrated to be mitigated by early stand density management by pre commercial thinning including an increase in individual tree growth response, improve the future merchantable yield and stand value, etc. (Cole 1975; Johnstone 1985; Johnstone and Cole 1988; Johnstone 2005; Johnstone and van Thienen 2011).

Scandinavian studies on scots pine (*Pinus sylvestris* L.) stands reported that timing of PCT has an impact on the dynamics of tree growth, competition between primary and secondary crop trees, and stand development (Petterson 2001; Varmola and Salminen 2007). Early thinning has been shown to increase diameter growth in variety of pine species (Varmola and Salminen 2004; Johnstone 2005; Huuskonen and Hynynen 2006; Ulvcrona et al. 2014). Long term studies of lodgepole pine in Alberta showed that early thinned stands had higher mean annual increment (MAI) compared to later thinned stands of the same stand age and productivity. However the early thinned stands had subsequent decline in increasing MAI while later thinned did not (Stewart and Salvail 2017). Furthermore, it has been reported that early thinning can create a possibility for early commercial thinning (Cole and Koch 1995). In addition, volume from first commercial thinning in early PCT scots pine stands were ~ 30% higher compared to late PCT stands (Huuskonen and Hynynen 2006). However, PCT in younger stands are more efficient and less costly due to relatively smaller diameters of trees (Riley 1973; Smith et al. 1986).

Western gall rust (*Endocronartium harknessii* (J.P. Moore) Y. Hiratsuka) is a widespread fungal pathogen in western Canada that affects hard pines (Mather et al. 2010, Fries et al. 2017). Pines are immediately infected by spores produced on pines without requiring to infect a different host first (autoecious). Temperature and moisture have a direct impact on the growth, distribution, germination, and subsequent infection of spores. Host distribution and survival will have a significant effect on changes in incidence and impact. If there is no limitation of suitable host species, impacts can be higher in ecozones where conditions become warmer and wetter (Chang and Blenis 1989; Myren 1994; Kliejunas et al. 2009). Infection frequency and intensity is also affected by regional stand dynamics such as wind speed, aspect, slope etc. (Bella and Navratil 1988). Western gall rust is distinguished by its globose to pear-shaped galls and, occasionally, hip cankers on susceptible hosts (Sinclair et al. 1987; Gross and Myren 1994). Cankers are most likely caused by branch galls that form next to main stem galls. Premature galls could be spindly rather than globose in shape (Hiratsuka et al. 1995). Swelling occurs after the initial infection, with branch galls enlarging as much as 1-10 cm and main stem galls reaching diameters of 20-30 cm (Sinclair et al. 1987).

Western gall rust has a low mortality rate in naturally occurring forests, but local epidemics have been documented (Peterson 1960). For example, in the western United States, rust infections mainly occur in "wave years," and these periods of high infection might ultimately result in a significant loss (Peterson 1971). Infections can result in either main stem galls or branch galls. Branch galls are more common, however they have very little effect on the growth of trees (Gross 1983; van der Kamp et al. 1994; Hiratsuka et al. 1995). However, stem galls can cause tree mortality (Gross 1983; Wolken et al. 2006). Stem galls may also lead to structural defects, leaving infected trees more susceptible to breaking during heavy snowfall and strong winds. The host may also be killed prior to stand rotation by the invasion of galls by secondary organisms (Byler et al. 1972; Sinclair et al. 1987; Gross and Myren 1994).

Western gall rust can infect pure lodgepole pine stands, and it can be damaging (Mather et al. 2010; Fries et al. 2017). Previous studies reported that stem gall size have significant impact on merchantability (Sattler et al. 2019) and mortality (Wolken et al. 2006). Large galls (specifically stem gall encirclements ≥ 50% w.r.t girth) especially which are present in the merchantable portion of the stem have serious impact on merchantability since they typically need to be removed during the manufacturing of timber (Gross 1983; Geron and Hafley 1988, Sattler et al. 2019).

The risk of western gall rust main stem infection declines as trees get older (Gross 1983). The probability of western gall rust infection is reported to decline with tree age and the likelihood of significant infection is between 15 and 20 years (Blenis and Duncan 1997; Blenis and Li 2005). It has been suggested that applying pre-commercial thinning by targeting infected trees may help reduce volume risk due to western gall rust (Hills et al. 1994). Moreover, delayed pre-commercial thinning until a reduction in the number of new stem infections may minimize losses due to WGR infections (van der Kamp and Spence 1987; Blenis and Duncan 1997).

The majority of long-term studies on lodgepole pine stands in Alberta focus on the impact of site productivity and thinning intensity on tree level and stand level yield in fire origin stands. These research have also attempted to investigate the effect of thinning timing on merchantability from a few experimental sites from fire origin stands, but the results are still unclear (Stewart et al. 2006; Stewart and Salvail 2017). There is, however, sufficient research from Scandinavian and European studies on the influence of timing of thinning in various pine species, and it appears to have a demonstrable impact on merchantability. Furthermore, there are only a few studies in Alberta that look at the effect of thinning and the timing of thinning on common pathogens like western gall rust, but they mostly look at the early stages of stand growth and don't tell us whether the results are still effective in later stages of the stands. In addition, it is still too early for making any conclusions without a local grasp of these data on an operational scale, because actual stand conditions can vary significantly unlike experimental sites. Therefore it is necessary to address the gaps to get more clear understanding of these aspects.

CHAPTER 2: RESEARCH CHAPTER

Introduction

The forest industry has quite an important contribution to Alberta's economy including GDP contribution (~ 1% of Alberta's GDP) and is a major employer in some municipalities across Alberta as it contributes around 27 per cent of all employment income in the most forestry-dependent community (Alberta Forest Economy 2021). However, the short to medium-term timber supply is expected to decline in the province (Schneider et al. 2010, Das Gupta et al. 2020) as a consequence of the cumulative effect of unexpected events from climate change such as insect pest attacks, wildfires, etc. (Perez-Garcia et al. 2002; Lusebrink et al. 2013; Shegelski et al. 2021). Despite this situation, government of Alberta intends to increase the timber harvesting and AAC on public lands by up to 13 % to promote the forest industry's viability (Government of Alberta 2020).

One possible solution for this timber supply issue is the application of more intensive silviculture practices such as pre-commercial thinning (PCT) on existing stands of important commercial conifer species such as lodgepole pine (Pinno et al. 2021). Intensive silviculture play a significant role in: (1) shortening individual stand rotation lengths, (2) securing the supply of timber in the face of threats from insects, fire, and diseases (Lieffers et al. 2020) and (3) maintaining the sustainability of forestry industry that creates jobs and contribute towards GDP.

PCT involves removal of poor quality noncommercial size tress in an effort to reduce competition and improve growth in the residual trees by the redistribution of available growing space and resources (O'Hara 1989). Thinning enhances diameter and height growth (Prescott et al. 2019), which in turn results in greater volume. In the residual trees, the size and persistence of crown are directly affected by available growing space (Johnstone and van Thienen 2004; Brockley 2011). Johnstone (2005) reported 20% greater live crown in thinned lodgepole pine stands compared to unthinned stands at 20 years of age. Moreover, reducing the number of trees aids in the crown expansion of dominant trees, facilitating their growth (Reid 2003; Reid 2004; Johnstone 2002; Ferguson et al. 2011), which in turn results in greater volume from bigger trees.

Lodgepole pine (*Pinus contorta*. var. *latifolia.)* is one of the most important commercial conifer tree species in Alberta comprising more than 41% (over 600 million cubic meters) of the provincial coniferous growth stock (26 % of the total growing stock in the province) (Government of Alberta 2012; Alberta Forest Economy 2021). After wildfires and logging, lodgepole pine often regenerates in highly dense stands. Such high densities decrease average stand height, diameter and merchantable volume but increase loss from mortality, length of rotations, and harvesting costs. However, a number of the detrimental consequences of excessive density in lodgepole pine stands have been demonstrated to be mitigated by early stand density management by pre-commercial thinning including an increase in individual tree growth response, improve the future merchantable yield and stand value (Cole 1975; Johnstone 1985; Johnstone and Cole 1988; Johnstone 2005; Johnstone and van Thienen 2011). In British Columbia, lodgepole pine stands thinned to 2500 sph had 7 times higher individual tree level total volume and 10 times higher merchantable volume compared to unthinned at 20 years of age, moreover the stand level total volume was ~35% higher in unthinned stands but the stand level merchantable volume was 20 times higher in thinned stands (Johnstone 2005). Similarly, in Finland scots pine (*Pinus sylvestris* L.) stands showed 15% greater mean diameter in thinned stands than that of the unmanaged stand at the stage of the first commercial thinning (Huuskonen and Hynynen 2006). In addition, canopy trees are observed to have greater response to thinning in even aged stands (Larson and Cameron 1986; Stewart and Salvail 2017).

Commercial thinning (CT) is also an important intensive silviculture tool to mitigate the current timber supply problem in lodgepole pine stands (Das Gupta et al. 2020). CT is growing in popularity in Alberta due to an effort to reduce timber supply gaps and because a significant amount of harvested area is becoming old enough that CT is an option. However operational application of CT requires specific stands characteristics. In general, stands which had herbicide treatment or PCT are observed to have higher potential for possible CT due to (Dewey et al. 2023) : (1) less tree size variability, (2) Merchantable size trees at the time of thinning and (3) greater crown in crop trees for more response to thinning. Moreover, the cost of CT will be higher if the proportion of suppressed trees or intermediate trees is greater. The potential for crop trees to be released from competition can also be reduced if there is a higher proportion of suppressed trees or intermediate trees in the stands. The ideal condition for CT would be the presence of more dominant and co-dominant trees rather than suppressed or intermediate trees (Dewey et al. 2023). Another important parameter for assessing CT potential is density variation. Even if the average density is acceptable, clumpy stands are often not suitable for CT because they have more varying tree sizes, leading to higher harvesting costs, a poorer growth response, and more blowdown potential. Therefore, reduced variability and more even spacing are better suited for CT (Dewey et al. 2023).

Moreover timing of pre-commercial thinning have been observed to have impact on growth and merchantability in mature stands. Early thinning has been shown to increase diameter growth in variety of pine species (Varmola and Salminen 2004; Johnstone 2005; Huuskonen and Hynynen 2006; Ulvcrona et al. 2014). Long term studies of lodgepole pine in Alberta showed that early thinned stands had higher mean annual increment (MAI) compared to later thinned stands of the same stand age and productivity (Stewart and Salvail 2017). However the early thinned stands had subsequent decline in increasing MAI while later thinned did not. Moreover, PCT in younger stands are more efficient and less costly due to relatively smaller diameters of trees (Riley 1973; Smith et al. 1986). It has been observed that doing early thinning enhances the possibility for early commercial thinning (Cole and Koch 1995). Volume from first commercial thinning in early PCT scots pine stands were ~ 28% higher compared to late PCT stands (Huuskonen and Hynynen 2006).

Western gall rust (*Endocronartium harknessii* (J.P.Moore) Y. Hiratsuka) is a pathogenic fungus that infects hard pines and it is widespread across the study region. Western gall rust infects lodgepole pine main stems and lateral shoots (Mather et al. 2010; Fries et al. 2017). While branch galls don't seriously affect growth, stem galls can cause tree mortality (Wolken et al. 2006; Gross 1983). However the probability of western gall rust infection declines with tree age (Gross 1983), especially after age 20 (Blenis and Duncan 1997; Blenis and Li 2005). Besides, silvicultural techniques, such as delayed pre-commercial thinning may minimize losses due to western gall rust infections since delayed thinning provide opportunity for more pre thinning infection (van der Kamp and Spence 1987; Blenis and Duncan 1997). It is also reported that thinned stands had ~12% higher stem infections compared to unthinned stands and hence it was recommended that PCT in heavily infected stands should be delayed or avoided due to the risk of understocking (Johnstone 1981; Bella 1985). Previous study from British Columbia reported that if stands were thinned without regard to the disease, the projected percent mortality would match the percentage of deadly infections at the time of thinning (van der Kamp 1994). Additionally, large galls (specifically stem gall encirclements ≥ 50% w.r.t girth) have a serious impact on merchantability since they typically need to be removed during the manufacturing of timber (Gross 1983; Geron and Hafley 1988;

Sattler et al. 2019). Furthermore, each 1% increase in main stem infection in young stands was projected to result in a 2 m^3 increase in volume loss during rotation (Woods et al. 2000). Hence it is necessary to understand the effect of stand management on western gall rust infections and severity to clarify these mixed results to make decisions on operations.

Most of the long term studies on lodgepole pine stands in Alberta mainly focus on influence of site productivity and intensity of thinning on tree level and stand level yield in fire origin stands (Stewart et al. 2006; Stewart and Salvail 2017). These studies had also tried to understand the effect of timing of thinning on merchantability from a few experimental sites from fire origin stands and the clarity on the outcomes are still unclear (Stewart et al. 2006; Stewart and Salvail 2017). However, there is enough literature from Scandinavian and European studies on the effect of timing of thinning in various pine species and it seems to have clear impact on merchantability. Additionally, there are only a few studies in Alberta that examine the effect of thinning and the timing of thinning on common pathogens such as western gall rust, but they mostly focus on the early stages of stand growth and provide no information on whether the results are still effective in later stages of the stands. Moreover, it is still too early to draw any conclusion without a local understanding of these findings from an operational scale since actual stand conditions can vary substantially. In addition, it is also important to see the effects on the stands after sufficient time has elapsed and in a mature stage when the stands are ready for a commercial thinning or final felling. Therefore, this study intends to address the above mentioned gaps in literature by answering the following research questions:

1. How does the timing of thinning affects individual tree level and stand-level merchantability?
2. Is the incidence and severity of Western gall rust (WGR) affected by timing of thinning?

Methods

Lodgepole pine stands in this study were located around town of Hinton in the Upper Foothills and Sub Alpine subregions of Alberta (Beckingham et al. 1996). The stands used in the study were all harvest origin and naturally regenerated during 1961-64 and they were categorized into pre-commercial thinning (PCT) and unthinned (control) based on treatment applied (Fig. 1). All the PCT stands were pre-commercially thinned from below and unthinned stands (11 stands) not treated. The PCT stands were operationally spaced at 1,800 to 2,500 trees/ha. The stands were selected based on their year of harvest and year of thinning (for PCT stands only). The crop tree species was lodgepole pine (~90%) with a lesser and variable amount of other species like white spruce (*Picea glauca* (Moench) Voss (Pinaceae)) and aspen (*Populus tremuloides* Michx.). PCT stands were further divided into two based on age at thinning. PCT_18 stands (11 stands) were thinned between the ages 17 -19 years and PCT_24 stands (11 stands) at 23-25 years of age. The elevation ranges from 1200-1550m (Table 1). The moisture regime is mostly mesic and nutrient regime medium (Table 1).

Ecosites were identified using "ecology_polygon.shp" provided by West Fraser, and field validation was done using identification of vegetation from the sites. Ecosite and natural subregion information was used to determine the moisture and nutrient regimes (Beckingham et al. 1996). Within each stands, six temporary fixed radius plots (5.64 m radius) were established at equal intervals of 50 m (Fig. 2). Plots were established at least 30 m away from roads, other stands, seismic line or creeks to avoid edge effects. Wetland areas or non-crop tree species dominated area were avoided.

(A) Unthinned (Control) (B) Pre-commercially thinned

Figure 1. (A) Unthinned stand and (B) Pre-commercially thinned stand in the study area.

For PCT stands, the thinning was observed to be evident in only some portions. Therefore, it was made sure that plots selected for sampling had presence of tree stumps from thinning to confirm evidence of thinning. Within each sampling plot, all the trees (DBH $\geq$ 5.1 cm-according to the criteria of permanent growth and yield sampling design in Alberta (Huang et al. 2015) were sampled for diameter at breast height (DBH), presence of stem galls and severity/encirclement of galls.

Table 1. Stand and site characteristics of pre-commercial thinning stands and unthinned.

UF: Upper Foothills; SA: Subalpine

Treatment	Elevation (m)	Natural sub region	Nutrient regime	Moisture regime	Year of Harvest	Year of Thinning
PCT_24	1302	UF	Medium	Mesic	1963	1987
	1229	UF	Medium	Mesic	1961	1986
	1269	UF	Rich	Mesic	1963	1987
	1295	UF	Medium	Mesic	1963	1986
	1287	UF	Medium	Mesic	1963	1987
	1258	UF	Medium	Mesic	1963	1987
	1302	UF	Medium	Mesic	1963	1987
	1249	UF	Medium	Mesic	1964	1987
	1283	UF	Medium	Mesic	1963	1987
	1369	UF	Medium	Mesic	1963	1987
	1344	UF	Medium	Mesic	1963	1987
PCT_18	1403	SA	Medium	Mesic	1961	1980
	1417	SA	Medium	Mesic	1962	1980
	1437	SA	Medium	Mesic	1961	1980
	1450	SA	Medium	Mesic	1962	1980
	1283	UF	Medium	Mesic	1964	1981
	1429	SA	Medium	Mesic	1962	1980
	1275	UF	Medium	Mesic	1964	1981
	1257	UF	Medium	Mesic	1963	1981
	1289	UF	Medium	Mesic	1964	1981
	1227	UF	Medium	Mesic	1963	1981
	1283	UF	Medium	Mesic	1964	1981
Unthinned	1543	UF	Rich	Mesic	1961	__
	1543	UF	Rich	Mesic	1963	__
	1508	SA	Medium	Mesic	1964	__
	1442	SA	Medium	Mesic	1962	__
	1312	UF	Medium	Mesic	1964	__
	1475	SA	Medium	Submesic	1961	__
	1380	UF	Medium	Mesic	1963	__
	1539	SA	Medium	Mesic	1963	__
	1268	UF	Medium	Mesic	1962	__
	1315	UF	Rich	Mesic	1961	__
	1292	UF	Medium	Mesic	1964	__

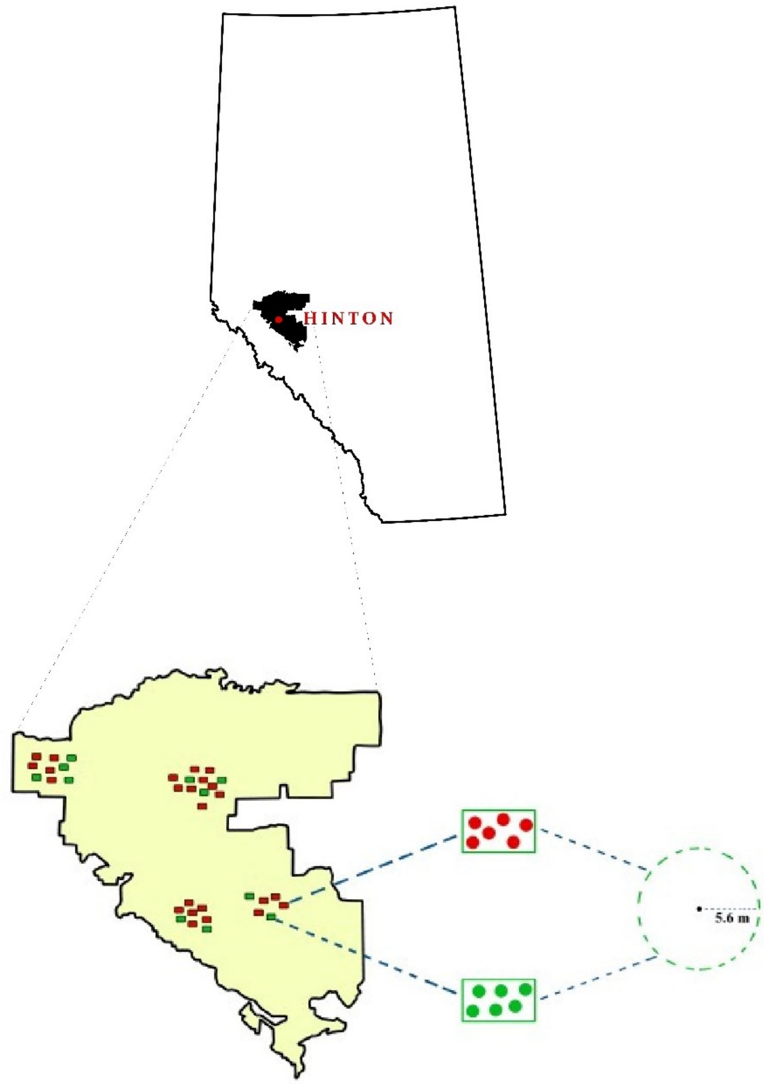

Figure 2. Location of the operational site and schematic distribution of the stands. The highlighted portion shows the Hinton wood products forest management area. Each rectangle represents one stand, and one dot represents one plot (5.64 m - 100 m²). Green dots indicate plots from unthinned stands and red dots indicate plots from PCT stands.

Stem gall encirclements were determined based on the percentage of stem girth it covers. Stem infections were classified based on encirclement of the stem gall (w.r.t girth of the tree at the point of infection) into low severity (< 50% of the girth) and high severity (≥ 50% of the girth). Western gall rust % was calculated as total number of infected trees /total number of trees for total infection rate comparison, while in case of severity it was total number of infected trees in the encirclement class/total number of infected trees. Five canopy trees (largest DBH trees) were selected from each plot to measure total height (HT) and height to crown base (HCB). HCB was defined as the position of the lowest whorl in a contiguous series containing at least one live branch. Live crown length (LCL) was calculated as H-HCB. For the stand-level assessment, the basal area, total volume, and merchantable volume of the trees were calculated using Forestry Tool-box, an Ms. Excel add-in for forestry data analysis was used (FGROW 2022). The toolbox uses volume equation developed by (Huang 1994) for total volume calculation. For merchantable volume the 15/11 merchantability criteria was used, where 15 cm is the minimum diameter outside bark at 15 cm stump height and 11 cm is the top diameter inside bark. This corresponds to a merchantable tree >13.5 cm DBH (Hossain et al. 2022).

Linear mixed effects Analysis of Variance (ANOVA) model fitted using *lmer* function from *lme4* package in R statistical software (Version 4.1.2, R Core Team 2021) was performed to determine the effect of treatment (fixed effect) on dependent response variables such as mean DBH, basal area/ha, total volume /ha, merchantable volume/ha, live crown length, height to diameter ratio and % western gall rust (proportion of infected trees). Block was set as random effect in the model. A significance level of $\alpha = 0.05$ was used for all statistical analysis. Whenever treatment effects were significant, pairwise comparison was performed using *pairs emmeans* function. Trees were divided into 5 diameter classes from <5 cm to 30 cm at an interval of 5 cm viz. (5.1-10.0 cm, 10.1-15.0 cm, 15.1-20.0 cm, 20.1-25.0 cm and 25-30.0 cm) for analyzing diameter class distribution in thinned and unthinned stands. The merchantable DBH of trees in this study is 13.5 cm and 20 cm DBH is considered to form a good quality large saw log.

Results

Basal area (avg. = 32.5 m²/ha, p = 0.75), total volume (avg. = 250 m³/ha, p = 0.65), merchantable volume (avg. =190 m³/ha, p = 0.17) and large sawlog volume (avg. = 100 m³/ha, p = 0.19) are not different in thinned stands compared to unthinned. However, the mean DBH is greater in thinned stands (avg. = 16.35 cm, p < 0.001) compared to unthinned stands (13.8 cm; Table 2).

Stand density (trees/ha) is lower in thinned stands (avg. = 1410 trees/ha; Table 2) compared to unthinned (2086 trees/ha), mainly due to the greater number of non-merchantable trees (DBH < 13.5 cm) in unthinned stands (1044 trees/ha, p < 0.001) compared to thinned stands (370 trees/ha; Fig. 3. B). However, the number of merchantable trees (avg. = 1040 trees/ha, p = 0.90) and larger diameter saw log class trees (avg. = 270 trees/ha, p = 0.10) are not different in thinned and unthinned stands.

Table 2. Summary of stand level properties in PCT_24, PCT_18 and unthinned; values are mean and standard error; Letters indicate significant differences between treatments (Type III Analysis of Variance Test -Satterthwaite's method).

Treatment	Density (Trees/ha)	Basal area (m²/ha)	Total Volume (m³/ha)	Merchantable Volume (m³/ha)	Mean DBH (cm)	Large Sawlog Volume (m³/ha)
PCT_24	**a**1448±48	**a** 32±1.10	**a** 265±10.1	**a** 212±10.0	**a**16.2±0.2	**a** 115± 11.6
PCT_18	**a**1371±50	**a** 30.5±0.8	**a** 247±8.5	**a**198±8.8	**a**16.5±0.2	**a** 116 ±11.0
Unthinned	**b** 2086±92	**a** 32.5±1.1	**a** 240±10.6	**a**158±11.0	**b**13.8±0.2	**a** 70 ±9.7
F value	17.60	0.28	0.43	1.84	10.67	1.70
p	<0.001	0.75	0.65	0.17	<0.001	0.19

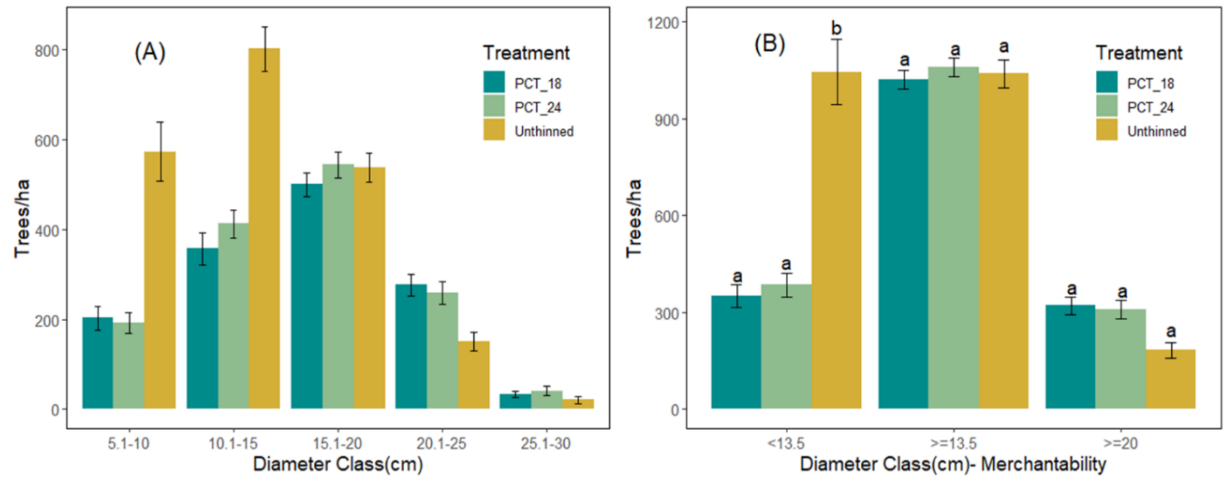

Figure 3. (A) Density of trees in PCT_24, PCT_18 and unthinned by diameter class .The x-axis represents diameter distribution of trees by diameter class and the y-axis represent trees per hectare measured at 2022. (B) Density of trees in PCT_24, PCT_18 and unthinned by diameter class (based on merchantability) .The x-axis represents diameter distribution of trees by diameter class and the y-axis represent trees per hectare measured at 2022. Error bar indicates standard error. Letters indicate significant differences between treatments (Type III Analysis of Variance Test - Satterthwaite's method).

The mean live crown length in thinned stands (avg. = 6.3 m, $p < 0.05$) are greater than unthinned (5.5 m; Fig. 4. A). However mean height-diameter ratio (HDR) is greater in PCT_24 stands (0.85, $p < 0.05$) compared to both PCT_18 stands (0.76) and unthinned (0.77; Fig. 4. B).

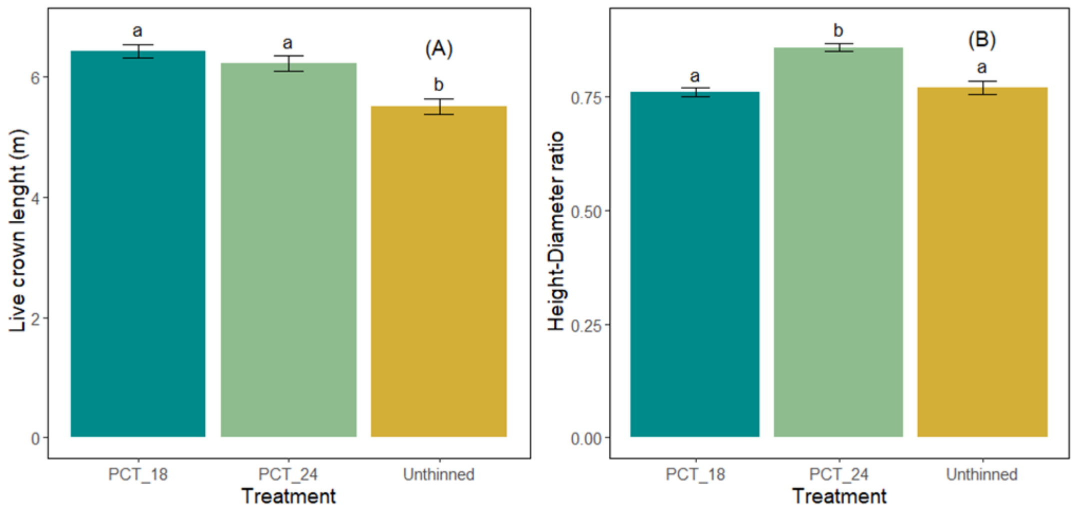

Figure 4. (A) Mean live crown lengths in PCT_24, PCT_18 and unthinned. (B) Mean height-diameter ratios in PCT_24, PCT_18 and unthinned. Error bar indicates standard error. Letters indicate significant differences between treatments (Type III Analysis of Variance Test - Satterthwaite's method).

Western gall rust infection rates (western gall rust %) are lowest in PCT_24 stands (22.1%, p = 0.01) compared to both PCT_18 (32.8%) and unthinned (32.6%; Fig. 5. A). In addition, trees with severe infections (western gall rust % from encirclement ≥ 50%) was less in PCT_24 stands (20.3%, p <0.05) compared to both PCT-18 (35.6%) and unthinned (31.2%; Fig. 5. B).

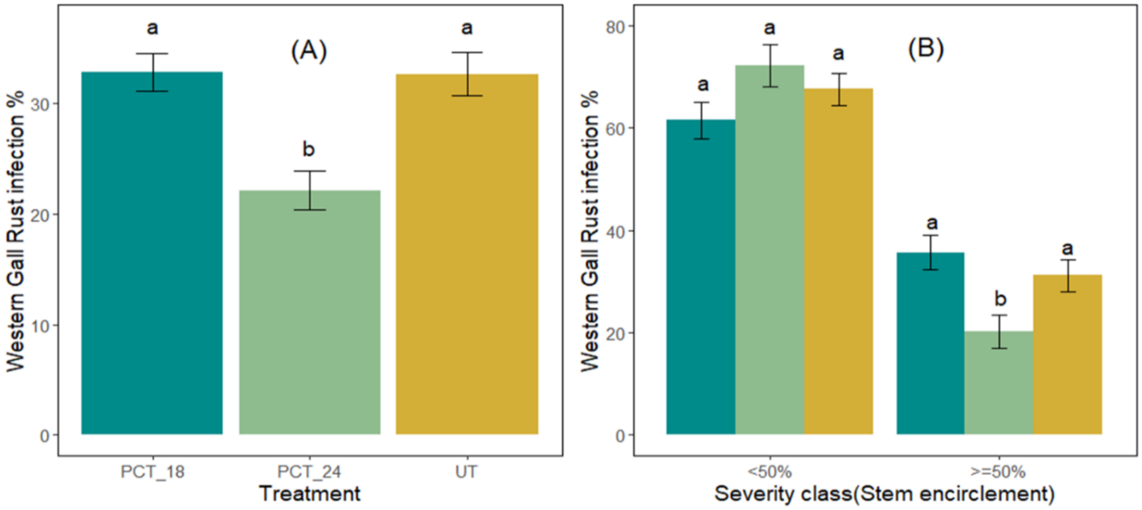

Figure 5. (A) Western gall rust stem infection proportion in PCT_24, PCT_18 and unthinned. Infection proportion is the number of trees infected w.r.t total number of trees. (B) Western gall rust stem infection severity (% stem encirclement) in PCT_24, PCT_18 and unthinned. Infection proportion is the number of trees infected w.r.t total number of infected trees. Error bar indicates standard error. Letters indicate significant differences between treatments (Type III Analysis of Variance Test -Satterthwaite's method).

Discussion

Pre-commercially thinned stands, regardless of timing showed greater average tree size (by up to ~15%) compared to unthinned stands approximately 40 years after treatment. However, timing of pre-commercial thinning had influence on western gall rust infections with later thinned stands having lower rates and severity of infection.

Total stand density is lower in thinned stands because of removal of tree during thinning and presence of higher number of small trees in unthinned stands. However, thinning results in a shift in diameter distribution since thinned stands in this study showed less positive skewness in the diameter distribution, which is a clear indication of the "chainsaw effect" or the selective removal of smaller and poorer trees (Hynynen 1995; Nogueira et al. 2015). This upward shift is also a direct consequence of improved diameter growth increment (Johnstone and van Thienen 2004; Brockley 2011). The cumulative effect of diameter growth increment as well as the upward shift in diameter distribution can be the reason for greater average tree size (by up to ~15%) in thinned stands compared to unthinned stands (Johnstone and van Thienen 2004; Huuskonen and Hynynen 2006; Ferguson et al. 2011). Despite faster tree growth and larger trees in thinned stands, total stand volume and merchantable volume is not different from unthinned stands due to the presence of greater number of small trees in unthinned stands and stand density reduction in thinned stands. However, greater diameter and height growth increments as well as the greater average tree size in thinned stands resulted in catching up with total and merchantable volumes of unthinned stands (Johnstone and van Thienen 2004; Prescott et al. 2019). Thinned lodgepole pine stands in British Columbia have been observed to exceed the merchantable volume of unthinned stands after 15 years of growth (Johnstone and van Thienen 2004). However, previous studies have also reported lower basal area and total volume in thinned stands compared to unthinned stands (Johnstone and van Thienen 2004), and that the volume loss at thinning is never made up by subsequent increased growth (Stewart and Salvail 2017).

Even though timing of thinning did not show any influence on merchantability in this study, previous studies in various pine species have observed the advantage of early thinning on the same (Varmola and Salmine 2004; Johnstone 2005; Huuskonen and Hynynen 2006; Ulvcrona et al.

2014). One possible explanation for the insignificance of timing of pre-commercial thinning on merchantability after 40 years could have been the subsequent decline in increasing MAI in earlier thinned stands, while later thinned did not. Hence, later thinned stands may have caught up with earlier thinned over time (Stewart and Salvail 2017).

Pre-commercially thinned stands in this study have greater potential for possible commercial thinning (CT) since they have (Dewey et al. 2023) lower variability in tree size, greater average tree size at time of CT, attained similar merchantable volume compared to unthinned stands at an earlier age and longer live crown lengths for greater future growth response. Moreover, high density in unthinned stands make them less suitable for CT because they become more prone to snow breakage and blowdown as they become taller with time. Hence the proportion of removal basal area over time decrease over time. Even if the average density in unthinned stands are acceptable, clumpiness in these are generally not suitable for CT due to higher cost of harvests and reduce growth response (Dewey et al. 2023). Hence, unthinned stands from this study are less suitable for CT unlike pre-commercially thinned stands due to their high stand density and clumpy stems. Additionally, the stand vigour factors such as live crown length, height or position in canopy before CT affect the response after. Trees with longer live crowns and greatest heights tend to be more vigorous. The post-thinning basal area growth was reported to be 30% higher by leaving same basal area of most vigorous trees instead of least vigorous trees (Larson and Cameron 1986). Hence thinned stands are likely to respond greater after CT due to longer liver crowns and top heights. Height-diameter ratio is a valid indicator of stand's stability and the average value should be below 90 to reduce the risk of blowdown (Dewey et al. 2023). Even though height-diameter ratios were higher in PCT_24 stands compared to PCT_18 stands, it isn't significant in the context of suitability for CT since both values fall under the recommended value for CT operations in

Alberta. However, if risk factors such as possible future impact from insect and pest damage is considered, PCT_24 stands are more suitable for CT than PCT_18 stands since western gall rust infection rate and severity are lower.

Timing of thinning had no influence on stand yield but did have an impact on western gall rust infection rate with PCT_24 stands having lower rates and severity of infection. Possible explanations for the lower western gall rust infection rates and severity in PCT_24 stands are: (1) a combination of delayed thinning and removal of all trees with stem galls should be able to lower post-thinning infection, (2) lower probability of western gall rust infections after 20 years since infections decline with tree age and the likelihood of significant infection is between 15 and 20 years, (3) delayed thinning provide opportunity for more pre thinning infection, such that the trees devoid of stem galls at thinning could be the most genetically resistant ones in the population and (4) the likelihood of a wave year occurring after thinning is reduced by delayed thinning (Blenis and Duncan 1997; Blenis and Li 2005). Apart from this a rapid change in western gall rust susceptibility in first 10 years of a tree was observed by (Blenis and Li 2005), which suggest that very early PCT is undesirable. This help to conclude that delayed PCT helps in lowering post thinning infections and loss due to western gall rust. Previous study from British Columbia reported that if stands were thinned without regard to the disease, the projected percent mortality would match the percentage of deadly infections at the time of thinning (van der Kamp 1994).

Attempting to eradicate diseases such as western gall rust from commercial pine stands is probably unrealistic. Management should instead strive to reduce their impact on final volume production and quality to acceptable levels. Even though late pre-commercial thinning helps reduce western gall rust infections, pre-commercial thinning in younger stands are more efficient and less costly due to relatively smaller diameters of trees (Riley 1973; Smith et al. 1986). Thus, delayed thinning can probably result in increased costs of operations and hence it should be considered only if the stands have considerable amount of western gall rust infections. Besides, delayed thinning helps in reducing losses due to western gall rust, such as volume removal during timber processing or breakage or blowdown, making them more suitable for subsequent commercial thinning compared to early thinned stands.

Hence for effective results, pre-commercial thinning should be applied with caution in the presence of western gall rust infection: (1) Thinning should be delayed to obtain most pre-thinning infections, (2) thinning should be applied targeting infected tree having stem galls or higher number of branch galls (Hills et al. 1994; Blenis and Duncan 1997) and (3) proper training and supervision is necessary while the operations are carried out. However, considering western gall rust infections, selective removal may result in non-uniform spacing due to the disease's random distribution in the stand (van der Kamp and Spence 1987; van der Kamp 1994). In such cases, it may be prudent to leave more trees on-site to compensate for any additional increase in tree mortality and long-term impact this may have on growth. This surplus may match the expected number of final crop trees, and this practice would also allow for commercial thinning later on (van der Kamp 1994).

Intensive silviculture and density management is not widely used in due to lack of understanding of yield benefits from thinning (Hossain et al. 2022) and policy barriers (Pinno et al. 2021). However, our study contributes to the clear understanding from an operational scale that PCT helps in obtaining similar merchantable yield at an earlier age compared to unmanaged stands but with greater average tree size and lower tree size variability, irrespective of timing of thinning, and greater potential for future commercial thinning. In conclusion, pre-commercial thinning should be considered for lodgepole pine stands in order to address timber supply issues in Alberta.

CHAPTER 3: SUMMARY AND MANAGEMENT IMPLICATION

The findings of this research provide a clear understanding of how pre-commercial thinning (PCT) impacts merchantability in lodgepole pine stands after enough time has passed. The most important finding is that there is noticeably greater mean DBH (Fig. 8) and lower tree size variability (Fig. 7) in PCT stands due to an upward shift in diameter distribution (Fig. 8), unlike unthinned stands. PCT helps in achieving similar volume yields (Fig. 8) compared to unthinned stands. However, PCT stands have more stand value due to less tree size variability and greater stem size.

The timber supply problem in Alberta be mitigated by commercial thinning since a significant amount of harvested area is becoming old enough for commercial thinning. Greater average tree size and less tree size variability make PCT stands more suitable for commercial thinning. In addition, PCT stands can respond better to commercial thinning due to longer live crowns (Fig.8). Moreover, unthinned stands were observed to have more clumpy stems in general and that can result is operational challenges and increased costs for commercial thinning application.

Western gall rust infection rate and severity are directly affected by the timing of pre-commercial thinning, and considering the disease, thinning late seems beneficial (Fig. 8). However, thinning late can lead to increased costs since trees have a greater DBH. Hence, in areas of high infection incidence, delayed thinning is likely prudent.

Therefore, it’s now clear that only pre-commercial thinning can help generate an increase in stem size and help sustain timber supply by providing more possibilities for commercial thinning. Thus, forest managers should consider the application of more pre-commercial thinning if the management goal is timber production.

Future research and recommendation

Future studies on lodgepole pine pre-commercial thinning should evaluate the combined effect of stand density, site productivity, and timing of thinning since most studies in Alberta mainly focus on density and site productivity, which have been shown to have a remarkable impact on tree and stand growth. It is also important to further evaluate the effect of thinning on western gall rust infections by considering different site conditions and ages at thinning.

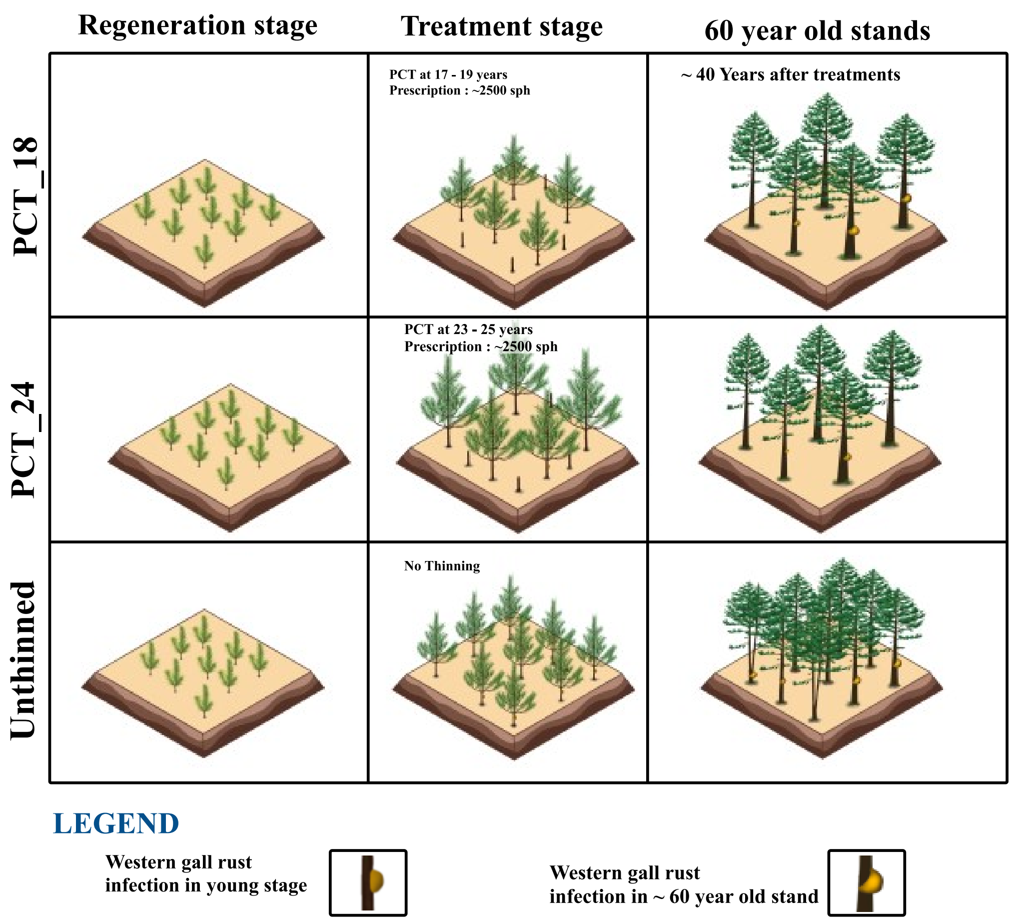

Figure 7. The diagram represents the visual summary of the effect of pre-commercial thinning and timing at thinning on merchantability and western gall rust infections in lodgepole pine stands compared to unthinned stands.

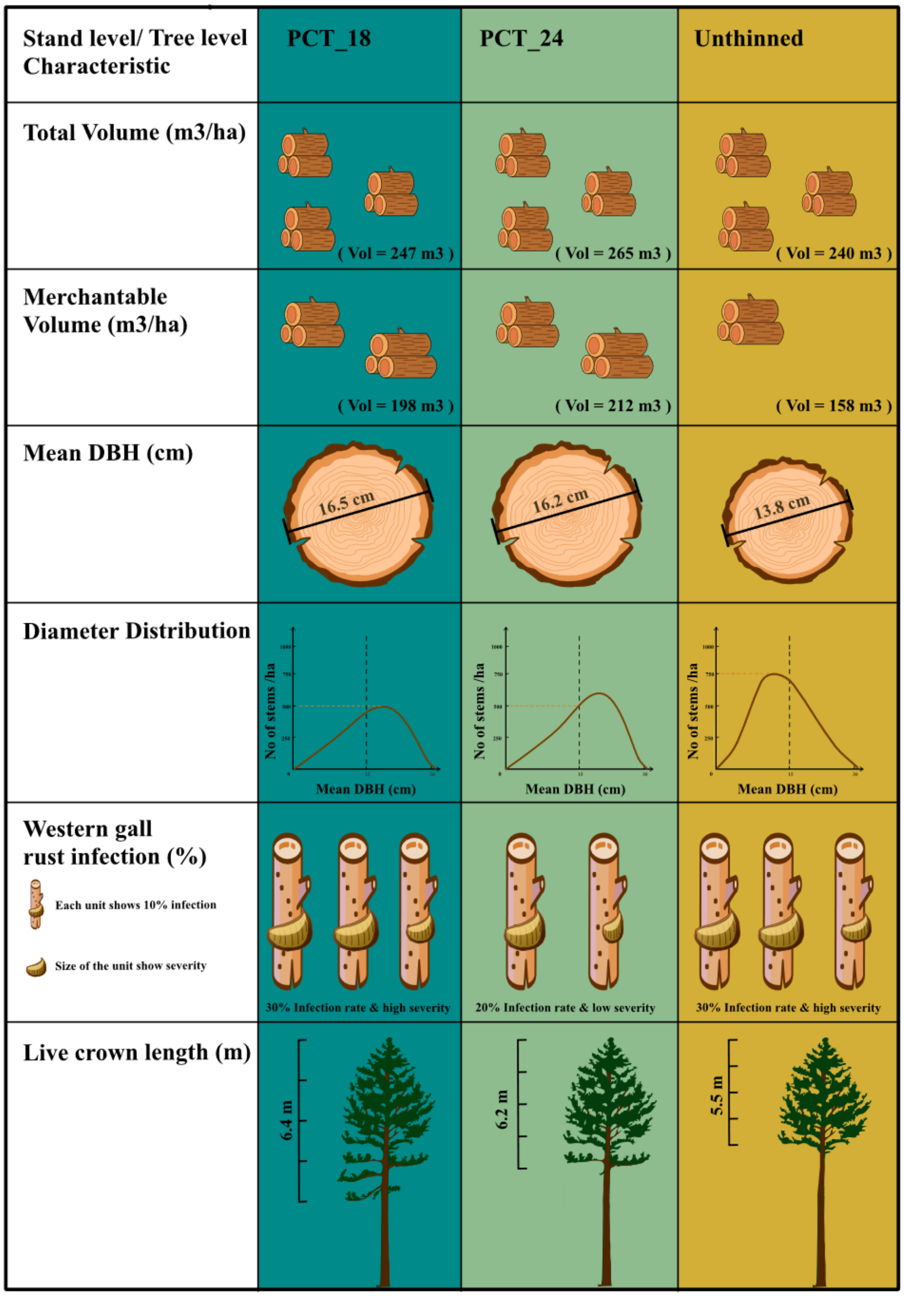

Figure 8. A detailed summary of results on the effect of pre-commercial thinning and timing of thinning on lodgepole pine stands compared to unthinned.

Literature cited

Alberta’s Forest Economy. 2021. A Handbook of Public Economic and Socioeconomic Accounts |Alberta Agriculture and Forestry, 2021. https://open.alberta.ca/dataset/bcec0091-cac0-4257-a8fd-bee57b8a0e6a/resource/001d198d-f495-4cf7-a10c-729f9e7e4887/download/af-albertas-forest-economy-2021.pdf. Retrieved Jul. 20, 2022.

Beckingham, J.D., Corns, I.G.W., and Archibald, J.H. 1996. Field guide to ecosites of west-central Alberta. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. Spec. Rep.9.540 p.

Bella, I. E., and Navratil, S. 1988. Western gall rust dynamics and impact in young lodgepole pine stands in west-central Alberta. Can. J. For. Res. 18(11): 1437-1442.

Bella, I. E. 1985. Western gall rust and insect leader damage in relation to tree size in young lodgepole pine in Alberta. Can. J. For. Res. 15(5): 1008-1010.

Blenis, P.V., and Duncan, I. 1997. Management implications of western gall rust in pre-commercially thinned lodgepole pine stands. Can. J. For. Res. 27(4): 603–608.

Blenis, P.V., and Li, W. 2005. Incidence of main stem infections of lodgepole pine by western gall rust decreases with tree age. Can. J. For. Res.35: 1314–1318.

Brockley, R. P. 2011. Effects of post-thinning density and repeated fertilization on the growth and development of young lodgepole pine. Can. J. For. Res. 35(6): 1952–1964.

Burns, R.M., and Honkala, B.H. 1990. Silvics of North America. Vol 1, Conifers. Agricultural Handbook 654. USDA. For. Ser., Washington, DC. 675p

Byler, J. W., Cobb, F. W., and Parmeter, J. R. 1972. Effects of secondary fungi on epidemiology of western gall rust. Can. J. Bot. 50(5): 1061–1066.

Chang, K.F., and Blenis, P.V. 1989. Survival of *Endocronartium harknessii* teloispores in a simulated airborne state. Can. J. Bot. 67(3): 928–932.

Chase, C. W., Kimsey, M. J., Shaw, T. M., and Coleman, M. D. 2016. The response of light, water, and nutrient availability to pre-commercial thinning in dry inland Douglas-fir forests. For. Ecol. Manag. 363: 98–109.

Cole, D.M. 1975. Culture of immature lodgepole pine stands for timber objectives. P. 536–555 *in* Management of lodgepole pine ecosystems,Vol. 2, Baumgartner, D.M. (ed.). Washington St. Univ., Pullman, WA.825 p

Cole, D.M., and Koch, P. 1995. Managing lodgepole pine to yield merchantable thinning products and attain sawtimber rotations. USDA For. Serv., Intermt. Res. Stn., Ogden, UT.

Daniel, T., Helms, J., and Baker, F. 1979. Principles of Silviculture; McGraw-Hill Series in Forest Resources; McGraw-Hill: New York, NY, USA.

Dewey, M., Schoonmaker, A., and Roth, B. 2023. Handbook for Commercial Thinning in Alberta. https://fgrow.ca/wp-content/uploads/sites/3/2023/02/Version-1-Handbook-for-Commercial-Thinning-in-Alberta.pdf (accessed February 25, 2023)

FGROW. Forestry Toolbox .2022. https://fgrow.ca/fri-subject-area/forest-management (accessed January 3,2022)

Fahlvik, N., Agestam, E., Ekö, P.M., and Lindén, M. 2011. Development of single-storied mixtures of Norway spruce and birch in Southern Sweden. Scand. J. For. Res. 26(S11): 36–45.

Fahlvik, N., Ekö, P.M., and Petersson, N. 2015. Effects of pre-commercial thinning strategies on stand structure and growth in a mixed even aged stand of Scots pine, Norway spruce and birch in southern Sweden. Silva Fenn.49(3)

Ferguson, D. E., Byrne, J. C., Wykoff, W. R., Kummet, B., and Hensold, T. 2011. Response of Ponderosa Pine Stands to Pre-Commercial Thinning on Nez Perce and Spokane Tribal Forests in the Inland Northwest, USA.

Fries, A. 2017. Damage by pathogens and insects to Scots pine and lodgepole pine 25 years after reciprocal plantings in Canada and Sweden. Scand. J. For. Res. 32(6): 459-472.

Geron, C., and Hafley, W. 1988. Impact of fusiform rust on product yields of loblolly pine plantations. South. J. Appl. For. 12(4): 226–231

Government of Alberta. 2012. Alberta's Forest Products Buyers' Guide.pp. 1–50.

Government of Alberta. 2020. Forest jobs action plan: A commitment to sustainable, long-term fibre access for forest companies. Published May 2020.

Gross, H.L. 1983. Negligible cull and growth loss of jack pine associated with globose gall rust. For. Chron. 59(6): 308–311.

Gross, H.L., and Myren, D.T. 1994. Western gall rust, *Endocronartium harknessii* (J.P.Moore) Y. Hiratsuka. Pages 106-107 *in* D.T. Myren, G. Laflamme, P. Singh, L. P. Magasi, and D. Lachance, eds. Tree diseases of Eastern Canada. Nat. Resour. Can., Can. For. Serv., Ottawa, Ontario.159p

Gupta, S. Das., Pinno, B.D., and McCready, T., 2020. Commercial thinning effects on growth, yield and mortality in natural lodgepole pine stands in Alberta. For. Chron. 96(2):111-120

Hills, S.C., Morris, D.M., and Bowling, C. 1994. Distribution and occurrence of western gall rust in jack pine stands. For. Chron. 70(6): 788-794

Hiratsuka, Y., Langor, D.W., and Crane, P.E. 1995. Western gall rust of hard pines. Pages 100-101 *in* A field guide to forest insects and diseases of the prairie provinces. Nat. Resour. Can., Can. For. Serv., Northwest Reg., North. For. Cent., Edmonton, Alberta. Spec. Rep. 3. 297p

Hossain, K.L., Lieffers, V.J. and Pinno, B.D. 2022. Thinning to meet sawlog objectives at shorter rotation in lodgepole pine stands. Can. J. For. Res. 52(6): 940–950

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

Huang, S. 2015. Minimum Standards and Suggested Protocol and Priorities for Establishing and Measuring Permanent Sample Plots in Alberta.

Huuskonen, S., and Hynynen, J., 2006. Timing and intensity of pre-commercial thinning and their effects on the first commercial thinning in Scots pine stands. Silva Fenn. 40: 645–662.

Hynynen, J. 1995. Predicting the growth response to thinning for Scots pine stands using individual tree growth models. Silva Fenn. 29: 5559.

Johnston, M., Price, D., L'Hirondelle, S., Fleming, R., and Ogden, A., 2010. Tree species vulnerability and adaptation to climate change: final technical report to Canadian Council of Forest Ministers, Climate Change Task Force. Sask. Res. Coun. Pub. No. 12416-1E10.

Johnstone, W.D. 1981. Pre-commercial thinning speeds growth and development of lodgepole pine: 25-year results. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, AB. Inf. Rep. NOR-X-237. 35 p

Johnstone, W.D. 1985. Thinning lodgepole pine. Pages 253–262 *in* D.M. Baumgartner, R.G. Krebill, J.T. Arnott, and G.F. Weetman, eds. Lodgepole Pine: the Species and its Management. Symposium Proceedings. Washington State Univ., Pullman, WA.

Johnstone, W.D., and Cole, D.M. 1988. Thinning lodgepole pine: a research review. Pages 160–164 *in* W.C. Schmidt, ed. Proc. Future Forests of the Mountain West: A Stand Culture Symposium, Missoula, Montana, Sept. 29 to Oct. 3, 1986. Gen. Tech. Rep. INT-243. USDA For. Serv., Intermountain Exp. Stn., Ogden, UT.

Johnstone, W.D., and F.J. van Thienen. 2004. A summary of early results from recent lodgepole pine thinning experiments in the British Columbia interior. B.C. Min. For., Res. Br., Victoria, B.C. Tech. Rep. 16.

Johnstone, W.D., and van Thienen, F.J. 2011. The effects of pre-commercial thinning on the growth and yield of lodgepole pine: 25-year results. B.C. Minist. For. Range, Forest Science Program, Kamloops, BC. 10 p

Johnstone, W.D. 2002. Thinning lodgepole pine in south eastern British Columbia: 46-year results. Res. Br. B.C. Min. For. Work. Pap. 63.

Johnstone, W.D. 2005. The effects of juvenile spacing on 7-year old Lodgepole pine in Central British Columbia. West. J. Appl. For. 20(3): 160–166.

Kliejunas, J.T., Geils, B.W., Glaeser, J.M., Goheen, E.M., Hennon, P., Kim, M.-S., et al. 2009. Review of literature on climate change and forest diseases of western North America. US Dept. Agric. For. Serv., Pac. SW Res. Stn., Albany, Calif. Gen. Tech. Rep. PSW-GTR-225.

Larson, B.C., and Cameron, I. R. 1986. Guidelines for thinning Douglas-fir: Uses and limitations. In Oliver, C.D., D. Hanley and J. Johnson (eds.) Douglas-fir: Stand Management for the Future, Col. For. Res., Univ. Washington, Seattle. p. 310–316.

Lieffers, V.J., Pinno, B.D., Beverly, J.L., Thomas, B.R., and Nock, C. 2020. Reforestation policy has constrained options for managing risks on public forests. Can. J. For. Res. 50(9): 855–861.

Lotan, J.E., and Perry, D.A.1983. Ecology and Regeneration of Lodgepole Pine, Agricultural Handbook No. 606. Forest Service, Department of Agriculture, Washington, DC, 51 pp.

Lusebrink, I., Erbilgin, N. and Evenden, M.L. 2013. The lodgepole× jack pine hybrid zone in Alberta, Canada: a stepping stone for the mountain pine beetle on its journey east across the boreal forest? J. Chem. Ecol. 39: 1209-1220.

Mather, W.J., Simard, S.W., Heineman, J.L., and Sachs, D.L. 2010. Decline of planted lodgepole pine in the southern interior of British Columbia. For. Chron. 86(4): 484-497.

McDougal, F.W. 1975. The importance of lodgepole pine in Canada. In: Baumgartner, D.M. (Ed.), Management of Lodgepole Pine Ecosystems, Symposium Proceedings, Washington, 9-11 October 1973. Washington State University, Cooperative Extension Service, Pullman, pp. 10-26.

Myren, D.T. (Editor), 1994. Tree diseases of eastern Canada. Nat. Resour. Can., Can. For. Serv., Sci. Sust. Dev. Dir., Ottawa, Ontario.

Nogueira, G.S., Marshall, P.L., Leite, H.G., and Campos, J.C.C. 2015. Thinning intensity and pruning impacts on Eucalyptus plantations in Brazil. Int. J. For. Res. 2015:168390

O'Hara, K.L. 1989 Stand growth efficiency in a Douglas fir thinning trial. Forestry. Int. J. For. Res, 62(4): 409-418.

Park, A., and Wilson, E.R. 2007. Beautiful plantations: Can intensive silviculture help Canada to fulfill ecological and timber production objectives? For. Chron. 83(6): 825–839

Perez-Garcia, J., Joyce, L.A., McGuire, A.D. and Xiao, X. 2002. Impacts of climate change on the global forest sector. Clim Change. 54: 439-461.

Peterson, R.S. 1960. Development of western gall rust in lodgepole pine. Phytopathology. 50(12): 876–881.

Peterson, R.S. 1971. Wave years of infection by western gall rust on pine. Plant Dis. Rep. 55: 163–167.

Pettersson, F. 2001. Impact of different cleaning regimes on the development of Scots-pine stands. *Skogforsk. Redogörelse*

Pettersson, N. 1993. The effect of density after pre-commercial thinning on volume and structure in *Pinus sylvestris* and *Picea abies* stands. Scand. J. For. Res. 8(1-4):528–539.

Pfister, R.D., and Daubenmire, R. 1975. Ecology of lodgepole pine, *Pinus contorta* Dougl. In: Baumgartner, D.M. (Ed.), Management of Lodgepole Pine Ecosystems, Symposium Proceedings, Washington, 9-11 October 1973. Washington State University, Cooperative Extension Service, Pullman, pp. 27-46.

Pinno, B.D., Thomas, B.R. and Lieffers, V.J. 2021. Wood supply challenges in Alberta–Growing more timber is the only sustainable solution. The For. Chron. 97(2): 106-108.

Pitt, D., and Lanteigne, L. 2008. Long-term outcome of pre-commercial thinning in northwestern New Brunswick: Growth and yield of balsam fir and red spruce. Can. J. For. Res. 38(3): 592–610.

Prescott, C., Demontigny, L., and Harper, G. 2019. Eighteen-year growth responses to thinning and fertilization of a height-repressed lodgepole pine stand in interior British Columbia. The For. Chron. 95(3): 207-221

Price, D.T., McKenney, D.W., Joyce, L.A., Siltanen, R.M., Papadopol, P., and Lawrence, K. 2011. High resolution interpolation of IPCC AR4 GCM climate scenarios for Canada. Nat. Resour. Can., Can. For. Serv. North. For. Cent., Edmonton, Alta. Inf. Rep. NOR-X-421.

Price, D. T., Alfaro, R. I., Brown, K. J., Flannigan, M. D., Fleming, R. A., and Hogg, E. H., et al. 2013. Anticipating the consequences of climate change for Canada's boreal forest ecosystems1. Environ. Rev. 21(4): 322–365.

R Development Core Team. 2021. R: A Language and Environment for Statistical Computing. The R Foundation for Statistical Computing, Vienna, Austria.

Reid, D., Silins, U., V.J. and Leiffers, V.J. 2003. Stem sapwood permeability in relation to crown dominance and site quality in self-thinning fire-origin lodgepole pine stands. Tree Physiol. 23(12): 833–840.

Reid, D.B., Leiffers, V.J., and Silins, U. 2004. Growth and crown efficiency of height repressed lodgepole pine: Are suppressed trees more efficient? Trees.18: 390–398.

Riley, L.F. 1973. Operational trials of techniques to improve jack pine spacing. Dep. Environ., Can For. Serv., Sault Ste. Marie, ON. Inf. Rep. 0-X-180. 26p.

Sattler, D. F., Goudie, J. W., and Reich, R. W. 2019. A module to simulate the impact of western gall rust (*Cronartium harknessii*) on merchantable volume and lumber yields for lodgepole pine (*Pinus contorta* var. latifolia) stands in British Columbia. Can.J.For. 49(11): 1379-1391

Schneider, R.R., Latham, M.C., Stelfox, B., Farr, D., and Boutin, S. 2010. Effects of a severe mountain pine beetle epidemic in western Alberta, Canada under two forest management scenarios. Int. J. For. Res. 2010

Shegelski, V.A., Campbell, E.O., Thompson, K.M., Whitehouse, C.M., and Sperling, F.A. 2021. Source and spread dynamics of mountain pine beetle in central Alberta, Canada. Can. Entomol. 153(3), 314-326.

Sinclair, W.A., Lyon, H.H., and Johnson, W.T. 1987.Diseases of trees and shrubs .48–49. Ithaca, NY: Cornell University Press.

Smith, David M. 1986. The Practice of Silviculture, 8th Edition. Wiley, New York, 527 pp.

Smith, D., Larson, B., Kelty, M., and P. Ashton. 1997. The practice of silviculture. John Wiley & Sons, Inc., New York. 766 pp.

Stewart, J.D., Jones, T.N., and Noble, R.C. 2006. Long-term lodgepole pine silviculture trials in Alberta: history and current results. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. and Foothills Model Forest, Hinton, AB.

Stewart, J.D., and Salvail, J.C. 2017. Evaluation of pre-commercial thinning of lodgepole pine from long-term research installations in Alberta. Nat. Resour. Can., Can. For. Serv., Can. Wood Fibre Cent., Edmonton, AB. Inf. Rep. FI-X-16

Ulvcrona, K., Karlsson, K., and Ulvcrona, T. 2014. Identifying the biological effects of pre-commercial thinning on diameter growth in young Scots pine stands. Scand. J. For. Res. 29(5):427–435 van der Kamp, B.J., and Spence, M. 1987. Stem diseases of lodgepole pine in the British Columbia interior following juvenile spacing. For. Chron. 63(5): 334–339.

van der Kamp, B.J. 1994. Lodgepole pine stem diseases and management of stand density in the British Columbia interior. For. Chron. 70(6): 773–779.

Varmola, M., and Salminen, H. 2004. Timing and intensity of pre-commercial thinning in *Pinus sylvestris* stands. Scand J. For. Res. 19(2): 142–151.

Wellner, C.A. 1975. The importance of lodgepole pine in the United States. In: Baumgartner, D.M. (Ed.), Management of Lodgepole Pine Ecosystems, Symposium Proceedings, Washington, 9-11 October 1973. Washington State University, Cooperative Extension Service, Pullman, pp. 1-9.

Wheeler, N.C., and Critchfield, W.B. 1985. The distribution and botanical characteristics of lodgepole pine: biogeographical and management implications. In: Baumgartner, D.M., Krebill, R.G., Arnott, J.T., Weetman, G.F. (Eds.), Lodgepole pine, the species and its management, Symposium proceedings, Spokane and Vancouver, May 1984. Washington State University, Cooperative Extension Service, Pullman, pp. 1-13.

Wolken, J.M., Blenis, P.V., and Duncan, I. 2006. Predicting survival of lodgepole pine stands infected with western gall rust. Can. J. For. Res. 36(4): 878–885.

Woods, A.J., Nussbaum, A., and Golding, W. 2000. Predicted impacts of hard pine stem rusts on lodgepole pine dominated stands in central British Columbia. Can. J. For. Res. 30: 476–481.

Appendix

A.1. Linear mixed effects Analysis of Variance (ANOVA) model results: Basal area

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	33.10	5.75
Residual	41.69	6.45
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	30.54	1.90	30	16.00	<0.001
TreatmentPCT_24	1.483	1.48	30	0.54	0.58
TreatmentUnthinned	1.943	1.94	30	0.72	0.47

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	23.61	11.80	2	30	0.28	0.75

A.2. Linear mixed effects Analysis of Variance (ANOVA) model results: Total volume

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	3587	59.89
Residual	3001	54.78
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	246.57	19.27	30	12.79	<0.001
TreatmentPCT_24	18.33	27.26	30	0.67	0.50
TreatmentUnthinned	-6.11	27.26	30	-0.22	0.82

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	2616.50	1308.20	2	30	0.43	0.65

A.3. Linear mixed effects Analysis of Variance (ANOVA) model results: Merchantable Volume

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	4260	65.27
Residual	2654	51.52
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	197.59	20.68	30	9.55	<0.001
TreatmentPCT_24	14.01	29.24	30	0.54	0.63
TreatmentUnthinned	-40.06	29.24	30	0.72	0.18

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	9774.60	4887.30	2	30	1.84	0.17

A.4. Linear mixed effects Analysis of Variance (ANOVA) model results: Large sawlog volume

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	3747	61.21
Residual	4238	65.10
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	116.43	20.12	30	5.78	<0.001
TreatmentPCT_24	-1.18	28.45	30	-0.04	0.96
TreatmentUnthinned	-46.07	28.45	30	-1.61	0.11

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	14443	7221.60	2	30	1.70	0.19

A.5. Linear mixed effects Analysis of Variance (ANOVA) model results: Mean DBH

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	1.86	1.36
Residual	2.85	1.68
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	16.45	0.46	30	35.65	<0.001
TreatmentPCT_24	-0.23	0.65	30	-0.35	0.72
TreatmentUnthinned	-2.64	0.65	30	-4.05	<0.001

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	57.42	28.71	2	30	10.06	<0.001

Pairwise comparison : Degrees-of-freedom method: kenward-roger

Confidence level used: 0.95

P value adjustment: tukey method for comparing a family of 3 estimates

contrast	estimate	SE	df	t.ratio	p.value
PCT_18 - PCT_24	0.23	0.65	30	0.35	0.93
PCT_18 - Unthinned	2.64	0.65	30	4.05	<0.001
PCT_24 - Unthinned	2.41	0.65	30	3.69	<0.05

A.6. Linear mixed effects Analysis of Variance (ANOVA) model results: Density (SPH)

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	55588	235.80
Residual	243960	493.90
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	1371.21	93.54	30	14.65	<0.001
TreatmentPCT_24	77.27	132.29	30	0.58	0.56
TreatmentUnthinned	715.15	132.29	30	5.40	<0.001

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	8590410	4295205	2	30	17.60	<0.001

Pairwise comparison : Degrees-of-freedom method: kenward-roger

Confidence level used: 0.95

P value adjustment: tukey method for comparing a family of 3 estimates

contrast	estimate	SE	df	t.ratio	p.value
PCT_18 - PCT_24	-77.30	132	30	-0.58	0.82
PCT_18 - Unthinned	-715.20	132	30	-5.40	<0.001
PCT_24 - Unthinned	-637.90	132	30	-4.82	<0.001

A.7. Linear mixed effects Analysis of Variance (ANOVA) model results: Density- Non-merchantable trees

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	70418	265.40
Residual	214242	462.90
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	350.00	98.22	30	3.56	<0.001
TreatmentPCT_24	34.85	138.91	30	0.54	0.80
TreatmentUnthinned	693.94	138.91	30	0.72	<0.001

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	6789056	3394528	2	30	15.844	<0.001

Pairwise comparison : Degrees-of-freedom method: kenward-roger

Confidence level used: 0.95

P value adjustment: tukey method for comparing a family of 3 estimates

contrast	estimate	SE	df	t.ratio	p.value
PCT_18 - PCT_24	-34.80	139	30	-0.25	0.96
PCT_18 - Unthinned	-693.90	139	30	-4.99	<0.001
PCT_24 - Unthinned	-659.10	139	30	-4.74	<0.001

A.8. Linear mixed effects Analysis of Variance (ANOVA) model results: Density- Merchantable trees

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	34072	184.60
Residual	47838	218.70
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	1019.70	61.82	30	16.49	<0.001
TreatmentPCT_24	39.39	87.43	30	0.45	0.65
TreatmentUnthinned	19.70	87.43	30	0.22	0.82

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	9711.30	4855.70	2	30	0.10	0.90

A.9. Linear mixed effects Analysis of Variance (ANOVA) model results: Density- Large saw log class trees

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	22101	148.70
Residual	27212	165.00
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	321.21	49.21	30	6.52	<0.001
TreatmentPCT_24	-10.61	69.59	30	-0.15	0.87
TreatmentUnthinned	-137.88	69.59	30	-1.98	0.05

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	132311	66156	2	30	2.4311	0.10

A.10. Linear mixed effects Analysis of Variance (ANOVA) model results: Tree level- Live crown length

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	0.33	0.57
Residual	0.67	0.82
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	6.41	0.20	30	31.98	<0.001
TreatmentPCT_24	-0.19	0.28	30	-0.69	0.49
TreatmentUnthinned	-0.91	0.28	30	-3.21	<0.001

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	7.70	3.85	2	30	5.72	<0.05

Pairwise comparison : Degrees-of-freedom method: kenward-roger

Confidence level used: 0.95

P value adjustment: tukey method for comparing a family of 3 estimates

contrast	estimate	SE	df	t.ratio	p.value
PCT_18 - PCT_24	0.19	0.28	30	0.69	0.77
PCT_18 - Unthinned	0.91	0.28	30	3.21	<0.05
PCT_24 - Unthinned	0.71	0.28	30	2.52	0.04

A.11. Linear mixed effects Analysis of Variance (ANOVA) model results: Tree level- Height-Diameter ratio

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	0.0043	0.066
Residual	0.0039	0.062
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	0.760	0.021	30	35.570	<0.001
TreatmentPCT_24	0.097	0.030	30	3.241	<0.001
TreatmentUnthinned	0.009	0.030	30	0.309	0.759

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	0.050	0.025	2	30	6.398	<0.001

Pairwise comparison : Degrees-of-freedom method: kenward-roger

Confidence level used: 0.95

P value adjustment: tukey method for comparing a family of 3 estimates

contrast	estimate	SE	df	t.ratio	p.value
PCT_18 - PCT_24	-0.097	0.030	30	-3.241	0.008
PCT_18 - Unthinned	-0.009	0.030	30	-0.309	0.948
PCT_24 - Unthinned	0.088	0.030	30	2.932	0.017

A.12. Linear mixed effects Analysis of Variance (ANOVA) model results: Western gall rust infection rate (%)

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	61.91	7.86
Residual	153.82	12.40
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	32.77	2.82	30	11.61	<0.001
TreatmentPCT_24	-10.67	3.98	30	-2.67	0.01
TreatmentUnthinned	-0.18	3.98	30	-0.04	0.96

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	1443.30	721.67	2	30	4.69	0.01

Pairwise comparison : Degrees-of-freedom method: kenward-roger

Confidence level used: 0.95

P value adjustment: tukey method for comparing a family of 3 estimates

contrast	estimate	SE	df	t.ratio	p.value
PCT_18 - PCT_24	10.67	3.99	30	2.67	0.03
PCT_18 - Unthinned	0.18	3.99	30	0.04	0.99
PCT_24 - Unthinned	-10.48	3.99	30	-2.62	0.03

A.13. Linear mixed effects Analysis of Variance (ANOVA) model results: Western gall rust infection severity- < 50% Encirclement

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	0.0	0.00
Residual	849.6	29.15
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	61.44	3.58	30	17.13	<0.001
TreatmentPCT_24	10.70	5.07	30	2.11	0.03
TreatmentUnthinned	6.08	5.07	30	1.20	0.23

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	3807.50	1903.70	2	30	0.28	0.75

A.14. Linear mixed effects Analysis of Variance (ANOVA) model results: Western gall rust infection severity- ≥ 50% Encirclement

Linear mixed model results

Random Effects:

Groups name	Variance	Std. Dev
Block (Intercept)	45.10	6.71
Residual	641.20	25.32
Number of obs: 198, groups: Block,33		

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
Intercept	35.58	3.71	30	9.57	<0.001
TreatmentPCT_24	-15.31	5.25	30	-2.91	<0.05
TreatmentUnthinned	-4.38	5.25	30	-0.83	0.41

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	5775.20	2887.60	2	30	4.50	<0.001

Pairwise comparison : Degrees-of-freedom method: kenward-roger

Confidence level used: 0.95

P value adjustment: tukey method for comparing a family of 3 estimates

contrast	estimate	SE	df	t.ratio	p.value
PCT_18 - PCT_24	0.23	0.65	30	0.35	0.93
PCT_18 - Unthinned	2.64	0.65	30	4.05	<0.001
PCT_24 - Unthinned	2.41	0.65	30	3.69	<0.05