Lodgepole pine and white spruce thinning in Alberta—a review of North American and European best practices

Enhanced Forest Management:
Implementation of Density Management Programs in Alberta

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1. EXECUTIVE SUMMARY

A substantial amount of managed forest in Alberta is entering a phase where commercial thinning is a legitimate option. However, forest managers in Alberta currently lack strong evidence to develop long-term adaptive thinning management strategies to address potential timber supply shortages that are likely to be exacerbated by various stresses on the forest. This literature review found that solid research on thinning in Alberta is under-represented relative to other jurisdictions. We evaluated and summarized the evidence regarding conifer stand density management with an emphasis on commercial thinning, and to a lesser degree pre-commercial thinning. We primarily sought to apply the information to the density management of white spruce and lodgepole pine. The use of stand density management diagrams as a tool for deciding where, when and how much to commercially thin was also reviewed. In areas of eastern North America, our work revealed that thinning spruce or fir stands from below, with tree removal levels from 30 to 40% of the basal area could increase the merchantable wood volume from 11 to 60 m^3 ha^{-1}, depending on stand age and intensity of thinning. Perhaps just as importantly, commercial thinning gives operators more flexibility to stabilize the wood flow. This thinning intensity range is slightly higher than what is recommended for jack pine (27%) stands in eastern Canada and slightly lower than current guidelines (43%) for lodgepole pine in the interior of British Columbia. Spruce–fir stands in Nova Scotia are recommended to have 32% to 47% removal. For Alberta conditions, and considering the risks, we conclude that commercial thinning basal area removal should be in the range of 25% to 40%, depending on a variety of factors such as species, wind firmness and insect or disease incidence and risk. Commercial thinning of closer to 40% will result in more commercial thinning volume but lower cumulative volume for the whole rotation, as compared to less aggressive (and potentially multiple) commercial thinning. Most of the evidence suggests that commercial thinning should be from below, at least for even-aged management of species with the same shade tolerance. Positive effects of commercial thinning at reducing stand vulnerability to stressors are limited to studies from eastern Europe. Our review reveals insufficient evidence from rigorous experiments to draw solid conclusions on this for Alberta. Thinning too aggressively and/or too late will increase the blowdown risk. The literature is fairly consistent in suggesting that live crown ratios should be >40% to maximize the chance of growth response and minimize the blowdown risk. Aggressive thinning may increase the risk of blowdown in the short term, but also may decrease the impacts of drought, both on growth and mortality. We expect that this is likely especially true if in addition to commercial thinning high densities are reduced during the reforestation phase. Drought is already having an increased impact on lodgepole pine and white spruce growth and mortality, especially in some areas. In cases where stands are also threatened by stressors such as drought, wind, and insect or disease outbreaks, thinning treatments likely offer the potential at limiting the overall risk, but localized knowledge and experience are critical. According to Moreau *et al.* (2022) for thinning to become part of normal forestry operations in Alberta, the first step should be to revisit the existing trials and studies, to link key stand attributes, such as density, structure, and composition to thinning prescriptions and stressors and their interactions). In parallel, there is a need for new thinning trials that include a variety of thinning treatments, to identify key stand attributes that can be linked with resistance and resilience to future forest stressors. Future thinning treatment trials in Alberta should likely be located across a fairly broad range of stand types in vigorous natural or managed stands, representing a continuum of homogenous (single species) to heterogeneous (mixed-species and strata) blocks. This would facilitate the full replication of a broader range of treatments; future focus on heterogeneous stands and potentially integrating reforestation practices to encourage more of these stand types is likely a wise step forward from a risk-mitigation standpoint. Multi-species stands may include multiple coniferous species plantings as well as mixed wood stands. It is intended that the information presented in this review supports new and ongoing research trials, G&Y model development, decision support tools, and practical density management recommendations for lodgepole pine and white spruce in Alberta.

2. INTRODUCTION

The forest industry is central to Alberta's economy, providing well-paying jobs for thousands of people, and making significant contributions to many Alberta communities for multiple generations. In 2019-20, a total of 14.5 million cubic metres of coniferous timber and 8.2 million cubic metres of deciduous timber were harvested, representing approximately $13.6 billion in economic output, $2.7 billion in labour income, $5.8 billion in the provincial GDP, and more than 31,500 jobs in Alberta (Alberta Forest Economy, 2021). Despite the Government of Alberta's attempts to increase the annual allowable cut (AAC) by up to 13% for Alberta's forestry companies[1], industry observers forecast that total Alberta tree harvesting, including regions regulated by the annual allowable, will decline in the years ahead. The causes of this expected decline have their roots in the devastating impact of the mountain pine beetle (*Dendroctonus ponderosae*; MPB) from 1999 to 2006, wildfires, land withdrawals (largely due to oil and gas development and resource mining such as sand and gravel), and climate change (Perez-Garcia *et al.,* 2002, Lusebrink *et al.,* 2013, Shegelski *et al.,* 2021). The cumulative effect of these factors has resulted in a continually shrinking operational land base for forest harvesting activities. Currently, there is interest from the industry in finding alternate ways to mitigate the projected timber supply shortage as demand for wood products stages a comeback (Stanturf and Mansuy, 2021).

Meeting these timber supply goals will require the establishment of more intensively managed plantations (Pinno *et al.,* 2021) and the application of density management treatments on existing stands to shorten rotation lengths and close harvesting gaps (White *et al.,* 2002; Gauthier *et al.,* 2015; Hossain *et al.,* 2022). Density management treatments are currently regulated through the Alberta Forest Management Planning Standard as defined in the Partial Harvest (non-clearcut) Planning and Monitoring Guidelines (Greenway *et al.,* 2006). This review focuses largely on stand density management through thinning in natural and managed stands of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. latifolia Engelm.) and white spruce (*Picea glauca* (Moench) Voss). Thinning treatments can facilitate a stable wood supply by filling age gaps in the timber supply through the capture of natural mortality and focusing growth on fewer trees which reach merchantable size sooner thereby reducing rotation ages (Oliver *et al.* 1996, Cochran and Dahms, 2000, Cameron, 2002, Jiří *et al.,* 2017). Pre-commercial thinning treatments are typically implemented within natural disturbance-origin or artificially regenerated (e.g., seeded) density-stressed stands during the sapling stage or early post-crown-closure stem exclusion phase of development (Newton, 2015). This involves the removal of the smallest non-commercial-sized individuals in a manner that attempts to redistribute the newly available growing space equitably among the residual crop trees. Commercial thinning treatments are prescribed during the semi-mature stage of stand development typically within managed or natural-origin stands previously subjected to pre-commercial thinning. Thinning can also be classified in terms of the crown class of tree removed or concerning the financial benefits of the operation.

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[1] Alberta Increases Annual Timber Harvest, 2020. https://albertawilderness.ca/20200506_goa_increases_aac/#:~:text=This%20week%2C%20the%20Government%20of,from%20a%20defined%20forest%20area

The obvious benefit of increasing the growth of merchantable trees may be the primary objective of thinning. Secondary to this stand-level objective in thinning includes reducing the time to merchantability and the final harvest cost, securing stable wood supply, enhancing stand stability and vigour, and reducing fuel loading (Zhang *et al.,* 2006, Cao *et al.,* 2008, Pitt *et al.,* 2013).

While thinning may improve the growth efficiency of residual trees, planning and implementation need to consider the existence of trade-offs between maximizing stand growth and volume risk. For example, gross production will be reduced if the stand is thinned too heavily (Figure 1). However, a positive trade-off will occur if merchantability standards are low and the thinning is light, the total yield may be higher as demonstrated in lodgepole pine in central Alberta where 50% of the mortality was captured (Das Gupta *et al.* 2020). It is therefore important to be able to establish when it is ideal to thin and if so, how intensively and to understand the nature of post-thinning responses. The post-thinning responses of merchantable volume may be described as parallel, convergent, or divergent to the volume yield of similar-size trees in unthinned stands (British Columbia (BC) Ministry of Forests 1999). A parallel response occurs when the volume of residual trees plus the volume of thinned trees (total volume) did not vary from the total volume present in an unthinned stand. A convergent response could result when one-stage or multiple-entry captures natural mortality, causing an increase in total volume recovered compared with unthinned stands (Gauthier and Tremblay, 2019). As for the divergent response, if the stand is thinned too heavily or if the treatment is performed too late, the total volume produced may be lowered in the thinned stand when compared to the unthinned stand (Houtmeyers and Brunner, 2020)

Alberta has large areas of lodgepole pine and white spruce cut blocks that have entered or are entering a phase where commercial thinning is an option. There is an opportunity to develop adaptive thinning treatments, which could form the basis for reducing rotation ages, accessing merchantable volume before final harvest, and adding value to end products (i.e., increasing sawlog to pulp proportion, appearance, and quality). However, to carry out such a treatment effectively, a review of existing literature is of value to inform those processes. This paper reviews the existing knowledge of the thinning treatments, especially as it may apply to lodgepole and white spruce-dominated stands in Alberta. Extra emphasis is placed on thinning intensity, the timing of interventions, methods and impacts on crop tree growth responses, and the associated risk factors. Although the geographical focus of this review is Alberta, information on this topic is more complete in other areas of North America, Scandinavia, and northern Europe, where there is a long history of density management. It is intended that the information presented, may support operations, ongoing and future research trials, and growth and yield (G&Y) model development.

3. THE EVOLVING SHIFTS IN ALBERTA'S STAND-TENDING PRACTICES

Forest conservation and management in Alberta has a long history that dates back to the early 20th century (Bott *et al.,* 2014). Until the early 1950s, reforestation in Alberta was generally left to nature as many of the cleared or degraded areas were regenerated naturally. Yet it became clear as early as the late 1940s that natural regeneration was less successful for most principal commercial species. This proved true for lodgepole pine and white spruce on most sites. The success story of forest regeneration in Alberta began with the period of adaptive regeneration promoted by Crossley (1955). Crossley advocated systematic clear-cutting with the idea of promoting long-term sustainable harvesting by creating stands with an even age-class distribution. Moreover, in Canada's northwestern boreal region, the annual amount of forested area burned by wildfires had risen steadily over the second half of the 20th century. Because lodgepole pine regenerates rapidly after a fire event, stands can quickly become overstocked (Smithers, 1961, Amoroso *et al.,* 2011), to the point where competition results in reduced tree growth and a decline in vigour, and mortality—including mortality from infestations of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (McIntosh and Macdonald, 2013). The scale and impact of the mountain pine beetle outbreaks challenged the *status quo* approaches to tending even-aged pure stands. Between 2005 to 2010, years after the peak of the most recent mountain pine beetle epidemic, conifers other than pine (Douglas fir (*Pseudotsuga menziesii* var. glauca Franco), white spruce and some broadleaf trees (trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.) have emerged as dominants, with lodgepole pine nearly absent in some regions (Oboite and Comeau, 2019). Trembling aspen regenerates in the stand after a fire and hastens density-dependent mortality (Reyes-Hernandez *et al.,* 2013).

By the early 2000s, the concept of thinning, which had been advocated by Quaite (1950) and Crossley (1955) was further promoted by the newly established Foothills Growth and Yield Association (Stewart *et al.,* 2006) following the presentation of the Provincial Enhanced Forest Management report and recommendations in January 1997. Before that time, a series of pre-commercial and commercial thinning trials had already been established in lodgepole pine stands by the Canadian Forestry Service and the Alberta Forest Service (Table 1). The trials were initiated in fire-origin stands throughout the Alberta foothills between 1941 and 1984 (Stewart *et al.,* 2006). The average timing of the data collected from these old trials was 34 years post-thinning treatment with the range of response data 19- and 58 years post-treatment. Regarding the thinning intensities, the thresholds defined as light, moderate, and heavy thinning vary among studies. The average ranges of the basal area percentage removed in the thinning treatments were light (<20%), moderate (20-35%) and heavy (>35). Unfortunately, many of the comparisons in the old thinning experiments were marred by inappropriate statistical designs, such as limitations in replication or site variability. Most of these trials involved one density management intervention or thinning prescriptions that were quite different from likely operational scenarios, lacked pre-treatment observations or documentation on the thinning prescription, and an absence of data on attributes of removed trees (volumes, piece sizes, etc.) which are essential for assessing the operational feasibility of thinning. Dewey (pers comm, September 19) suggested it would be necessary to exercise great care in interpreting data from trials with only one density management intervention over time. Without multiple interventions on at least some of the densities, the single thinning may only defer stagnation into the future, and results are likely to be misleading. Furthermore, ideally, research would attempt to reflect the fact that in an operational context, there is an opportunity to respond to actual conditions, depending on how the stands have developed. For example, in reality, density management prescriptions can be adjusted, and parts or all of a stand can be dropped from treatment. Research designs should attempt to mimic this operational flexibility. The historic trials described above lead us to suggest a need for new thinning trials in Alberta that capture a range of conditions around the operational optimum that can be used to characterize tree and stand responses to thinning and provide data for future growth and yield modelling efforts.

In keeping with the above, several pre-commercial (Pinno *et al.,* 2012, Dempster, 2022) and commercial (e.g., Das Gupta *et al.,* 2020) thinning research trials in lodgepole pole pine were recently initiated, largely focused on the foothills subregions in Alberta following a more robust statistical procedure. However, the information on thinning of lodgepole pine stands gathered from current experiments in Alberta does not provide a sufficient baseline for developing a thinning practice for the species. While new studies with well-balanced designs can provide the data needed to develop practical thinning guidelines and make better-thinning decisions, they may take some time and delay before obtaining results (Michel Huot, personal communication, November 13, 2022). Michel provides some recommendations, suggesting a work-in-progress situation where existing data are considered first while waiting for more robust data from new studies. Examples of such surveys exist in Nova Scotia for red spruce and balsam poplar, where knowledge and experience in the existing operational handbooks are utilized for their estimates of growth and yield (Kent *et al.,* 2012).

4. APPROACHES TO THINNING DECISIONS

4.1 How much to remove

The decision whether to thin and if so when and how heavily, must ultimately be guided by the intended volumetric yield, end-product quality and value and ecosystem service outcomes (Smith and Brennan, 2006, Newton, 2021). Strong common threads run through most of the reviewed literature. Particularly where dense, even-aged, and homogenous (single-story) stands are concerned, the indications are that individual residual crop trees may benefit from heavier thinning. A thinning experiment in naturally regenerated jack pine (*Pinus banksiana* Lamb.) in New Brunswick with three pre-commercial thinning intensities showed 75% and 20% differences in tree diameter and merchantable stem volume between light (>20%) or moderate (40%) thinning and heavy (70%) thinning (Zhang *et al.,* 2006) after 34 years (stand age 59). Soucy *et al.* (2012) investigated a long-term thinning experiment in upland black spruce in Quebec's north shore region. The stands were established with three thinning intensities: 0%, 25%, and 50% of the total basal area removed. After 15 years, heavily thinned plots showed a net stand merchantable volume increment 33% greater than that of the unthinned plots. When a spruce budworm (*Choristoneura fumiferana* Clemens) outbreak affected the site, Soucy *et al.* (2012) found the heavily thinned plots maintained a superior tree growth rate and did not show senescence mortality that was common for balsam fir (Morin, 1994, Pothier *et al.,* 2012), allowing stand volume to catch up to that of the unthinned plots after 33 years. However, some research from Scandinavia (e.g., Nilson *et al.,* 2010, Bergh *et al.,* 2014) has shown that a series of light thinning treatments repeated at frequent intervals of thinning (e.g., every 5 years) can limit density-induced mortality and yield a higher quality end-products than heavy, single-entry thinning (i.e., removing more than 50% of basal area). These positive outcomes were generally linked to the long-term responses of crown architecture to repeated light thinning, resulting in higher leaf/sapwood ratios for trees consistently released from the competition (D'Amato *et al.,* 2013).

Five-year multiple entry timings with commercial thinning appear to be a classical example of a selection treatment, which is often aimed at young uneven-aged management and irregular forests. Since Alberta's forests are primarily even-aged and selection harvest is not appropriate, these frequent commercial thinnings are not likely to be applicable. In general, we noted that the most effective commercial thinning method in the northeastern portion of North

America in terms of large tree response, sawlog volume, and stand value is thinning mainly from below (Kent *et al.,* 2012, Gauthier *et al.,* 2015, 2019, Boivin-Dompierre *et al.,* 2017, Wagle *et al.,* 2022) or crown (Olson *et al.,* 2014), with tree removal level up to 50% (30 to 40% of basal area) for spruce or fir stands. This intensity range is somewhat heavier than what Gauthier and Tremblay (2019) recommend (27%) for jack pine (*Pinus banksiana* Lamb.) stands in eastern Canada but corresponds to what current guidelines suggest (43%) for lodgepole pine in the interior of BC (BC Ministry of Forests, 2021) and for spruce–fir stands (32 to 47%) in Nova Scotia. Moulinier *et al.* (2015) also demonstrated there is an upper limit to thinning intensity of jack pine in eastern Canada (64% basal area removal) above, which thinning would no longer benefit residual stand volume. Taken together, the results of these trials would appear to indicate that a high thinning intensity produces larger trees on average, while a lower intensity maximizes volume production per hectare. The results do, however, provide other useful insight into the overall effects of thinning conifers and therefore may be useful in providing some directions for further thinning intensity trials in different geographic regions. For instance, the 30 to 40% minimum basal area removal proposed by Gauthier *et al.* (2015, 2019) may correspond to greater than 4 competitors removed per residual tree crop (in a stand with an initial stocking density of 2,500 stems ha^{-1}). However, this would very much depend on the vegetation management that took place during the reforestation phase.

4.2 When to thin

The question of when to thin and the form is also important, as poor timing of thinning can have serious consequences for the stand. Indeed, McGrath *et al.* (2009), Bjelanovic *et al.* (2021), and Hawe and Short (2016) point out certain positive silvicultural and economic aspects of avoiding late-entry pre-commercial or commercial thinning. Late-entry commercial thinning in general has been shown to produce windthrow problems enough to finally end up with a clearcut instead of a partial cut. A typical example is the damage caused by Hurricane Juan on commercially thinned stands in central Nova Scotia in September 2003. In an attempt to determine whether stand conditions affected damage levels in commercially thinned stands, both positive and negative relationships were discovered to exist between the thinning intensity, stand age at thinning, the slenderness of the trees and wind damage (McGrath *et al.,* 2009).

While one proposed benefit of early intervention is to maintain growth on high-quality residual stems (Kanninen *et al.,* 2004), a further benefit may be that the residual trees are less susceptible to attack by disease and insect pests (Traugott and Dicke 2006). Traugott and Dicke (2006) go on to recommend the following basic commercial thinning guidelines in pine stands intended for sawlog timber production in the southeastern region of the United States: 1) natural pruning is at least 5.5 m in height, 2) mean stand diameter at breast height (DBH) (1.3 m aboveground) is at least 15 cm, 3) the last 3 years annual growth rates are less than 10 percent, and 4) average total tree height is at least 12.2 m. The need for a first thinning can be sooner on land with a high site index compared with land that has a low site index (Wright, 1976, Smith and Brennan, 2006). It is thought that the significance of the site index's effects in influencing the timing of the first thinning is better understood when considered with stocking density (Varmola and Salminen, 2004). Even on the best sites, the timing of the first thinning can be delayed in stands with poor survival and/or low initial planting density. Site occupancy and stand differentiation are often delayed under these conditions, and maintenance of high crown ratios sustains better diameter growth than can be attained in more dense stands (Choi *et al.* 2008).

We have not seen much of a research focus on the influence of rotation length and the use of additional thinnings on the timing and form of the first thinning. However, yield simulation work by Nebeker *et al.* (2015) has shed some light on the relationships. These simulations verified earlier observations about the time of thinning and site index and stand density relationships. The overall principles that determine which should be removed during thinning have been well documented (Pukkala and Miina, 1998, Nebeker *et al.,* 2015, Pukkala *et al.,* 2015). Pukkala and Miina (1998) optimized a tree selection rule which was based on the effect of tree removal on the competitive positions of remaining trees. In their work, it was found that it was optimal to thin from above (remove large trees). Theoretically, it may be thought that the removal of the largest trees in a stand equates, to some extent, to the removal of the best producers. Concerns about decreasing growth arising from repeated removal of the largest trees in the stand were raised in the early 20th century and intensively discussed. Even later there has been discussion about the risk of growth losses due to negative genetic selection after repeated thinning from above (Nilsson *et al.,* 2010). In addition to potential risks associated with genetic selection, there is some evidence from the Scandinavian (Wallentin and Nilsson, 2014) and eastern North America (Nebeker *et al.,* 2015) that thinning from above will increase the residual stands risk for windthrow. It was reported that a retained cubic metre of trees in a small diameter class has higher stem volume production than a retained cubic metre of a large diameter class (Mäkinen and Isomäki, 2004). Nebeker *et al.* (2015) and Pukkala *et al.* (2015) proposed a more straightforward approach to optimizing tree selection for thinning: the criteria of the cutting rule were the tree's health condition, stumpage value, value increment, and the effect of removal on the growth of surrounding trees.

4.3 Which trees should be removed in thinning?

As stand densities increase, the method used to remove trees becomes more important due to lasting effects on the residual growing stock. While mechanical thinning (e.g., row or corridor thinning), where trees are removed strictly based on spacing with little or no regard to the crown position is accepted, thinning should primarily target the removal of future crop tree competitors (Nebeker *et al.,* 2015, Hawe and Short, 2016). Most comparisons (e.g., Volkova *et al.,* 2017) have shown that mechanical thinning plus selective thinning (trees are removed individually based primarily on spacing and stem quality) results in higher growth rates and better stem quality compared to pure mechanical-type thinning. There is, however, a downside to this practice, because mechanical thinning can potentially expose the stands to damaging agents such as wind and ice. In keeping with the above, Nebeker *et al.,* 2015, go on to advise that in stands with a high incidence rate of diseased or malformed trees, mechanical thinning in the form of rows or corridors would be inappropriate as the treatment often leaves too many defective trees at the expense of better ones. In contrast, trees removed in the selective thinning are those in the lower crown classes and poorly formed or diseased trees. For that reason, post-thinning mortality (with a combination of mechanical and selective thinning) should be less than that for row or corridor thinning alone and comparable to that for selective thinning alone

5. COMMERCIAL THINNING OF INDIVIDUAL SPECIES

5.1 Lodgepole pine

Little debate surrounds the thinning needs of overly stocked lodgepole pine regeneration, where early and heavy thinning are commonly recommended for rapid diameter growth (Ballard and Long, 1988). Early, light, and frequent thinnings (two or three entries) have also been recommended for maximum pulpwood plus saw timber production in Scots pine in northern Europe (Nilsson *et al.,* 2010). Dennis et al.'s (2010) guidelines on maximizing the resistance of both young and mature lodgepole pine before mountain pine beetle attacks are highly practical in their application. The strategy is to remove no more than 25 percent of the stand's basal area in commercial thinning during each cut and to carefully monitor stands to ensure the proper timing of the necessary re-entries. Maintain average stem diameters of > 20 cm and stand densities of >18 square meters of basal area per hectare. There may also be good reasons for starting to thin young lodgepole pine later than the standard pre-commercial thinning age (e.g., after age 15), notably where the standing density of the trees in such a thinning is low. If lodgepole pine thinning is delayed at ages > 40 years, it will need to be heavier, so that the stands can return to the correct growing stock level, consistent with that of the standard pre-commercial thinning age (Nebeker *et al.,* 2015, Nilsson *et al.,* 2010).

Publications such as *Thinning Southern Pines* (Demers *et al.,* 2013) and *Southern Pine Density Management* (Nebeker *et al.,* 2015) also provide intensity recommendations based on the number of stems per ha, basal area and/or volume removal. Demers *et al.* (2013) outlined the methodology to reduce stocking, including the systematic removal of entire rows of trees (trails) to facilitate access, combined with the selection of future crop trees and related competitor removals. Only British Columbia provides an interim operational manual or guidance for commercially thinning lodgepole pine in Canada (Pavel, 2021). This thinning type is based on current practices in BC's interior where timber is removed on 5 m wide trails, measured bole to bole, and established every 20 m. The criterion for selecting stands suitable for thinning applications involve stand age, site index, stand density, basal area, and merchantable volume per hectare. The operational manual for commercial thinning in interior British Columbia (Pavel, 2021) provides the optimal thinning ages by site index for the most common species. For lodgepole pine, there seems to be a general agreement that stands with a site index of 16 to 26m are good candidates for commercial thinning (BC Ministry of Forests, 2021). The principal thinning method is "systematic", with 5 m wide access tracks and a 15 m selection zone. The 15 m strips between trails are then thinned from below to enhance the volume and value of the residual crop trees at the time of final harvest. With thinning from below, the lower crown classes are removed to favour the most vigorous trees in the stand. Trees 'thinned from below' can also include 'quality thinning' where dead, damaged, and diseased trees are removed to utilize tree mortality losses while improving the health, resilience, and growth of the remaining trees.

5.2 White spruce

Since it is slower growing and more shade-tolerant than lodgepole pine, white spruce is generally thought to require a later first thinning than lodgepole pine (Pelletier and Pitt, 2008). The inception of programs such as the Green River thinning trials in naturally regenerating balsam fir

(*Abies balsamea* [L.] Mill.)-dominated stands in northwestern New Brunswick (Pitt *et al.,* 2013, Plamondon *et al.,* 2013, Warren *et al.,* 2013) and the University of Maine's Commercial Thinning Research Network (CTRN) and Austin Pond studies in spruce-fir (*Picea-Abies*) stands in the northeastern US (Bataineh *et al.,* 2013, Olson *et al.,* 2014, Kuehne *et al.,* 2016), as well as studies in Norway spruce (*Picea abies* L.) in northern Europe (Mäkinen and Isomäki, 2004, Nilsson *et al.,* 2010, Krajnc *et al.,* 2019), have provided further insights regarding thinning needs. Based on long-term data generated in the Green River thinning trials, Pitt *et al.* (2013) demonstrated that thinning balsam fir to a nominal spacing of 1.8 m (2990 sph) offered the best balance between individual tree growth and adequate density for maximizing per-hectare production. Another study in New Brunswick has shown that early single-entry thinning (age 19) increased quadratic mean diameter and mean merchantable volume per stem at the end of the observation period by 10% and 24%, respectively, over unthinned stands; a second thinning removed an additional 48–64 m^3 ha^{-1}, increased diameter and resulted in volume gains of 25% and 71%, respectively (Pelletier and Pitt, 2008). In some cases, delaying the first thinning to 34 years resulted in marginal differences with early thinning at age 19 or 24, but the risk of windthrow increased (Achim *et al.,* 2005). One note of caution, however, is that the study by Achim *et al.* (2005) was conducted on red spruce (*Picea rubens* Sarg.) plantation, making the responses more relative to the site conditions. Wagle *et al.* (2022) report the results of a replicated spruce-fir thinning trial in northern Maine, USA. The stand used was derived from natural regeneration either after shelterwood removal cutting or salvage clearcutting following the eastern spruce budworm (*Choristoneura fumiferana*) outbreak in the 1970s-1980s. After 16-18 years from treatment, they found that delaying commercial thinning in young spruce-fir stands did not enhance total yield and stand value. Thinning from below enhanced average tree size and sawlog production, while thinning from above had detrimental effects on tree size and total yield (Zeide, 2001, Clune, 2013).

The White Spruce Management Guidance for DNR Forestry-Administered Lands by Schnell *et al.* (2012) recommended pre-commercial thinning from below to a basal area of 25–27 m^2 ha^{-1} around 20–25 years. It went on to suggest a commercial thinning between 30 and 50 years if the live crown ratio of both the dominant and co-dominant trees is more than or equal to 40%. Stands allowed to grow beyond this stage may develop crown proportions that may be too constricted to fully respond to commercial thinning. In some experiments, the difference in volume production between conventional thinning from below and thinning from above has been small and insignificant. Given the same basal area removal in each cutting, Eriksson and Karlsson (1997) found a slight growth reduction (6%) in Norway spruce stands after repeated thinning from above compared with thinning from below. In general, there is little literature regarding the thinning of white spruce in Alberta (e.g., Bjelanovic *et al.,* 2021, Comeau, 2021). White spruce commercial thinning trials in Alberta are scarce with incomplete information for developing province-specific guidelines (especially in managed stands), there is growing evidence from eastern Canada that thinning managed stands from below to basal areas in the range of 22 to 35 m^2 ha^{-1} could increase the merchantable wood volume from 11 to 60 m^3 ha^{-1}, depending on stand age and intensity of thinning (Stiell, 1970, 1980, Pelletier and Pitt, 2008, Dupont-Leduc *et al.,* 2020).

6. RISK FACTORS

Besides the typical trade-offs between wood yield and wood quality, thinning can involve other trade-offs such as those between wood quality and environmental factors or damaging organisms. Accounting for the risks of wind, snow, and the possibility of increased incidence of insects and disease in management will affect the optimal choice of the thinning regime in terms of financial returns; it should be recognized that most stands will face at least one or more of these risks at some point through their rotation and therefore these risks must be considered thoughtfully when developing density management programs. Consideration of the risks will become increasingly useful, as additional information can help improve the thinning decision-making process. This consideration will require a fundamental shift in how current thinning decisions are viewed: to help mitigate risk and uncertainties, either plans should be revised as new information becomes available or the possibility of adaptation should be accounted for in preparing the plans. In this section, we conduct a brief review of some of the risks and stresses in relation to thinning regimes and highlight how risk management implies trade-offs

6.1 Wind and snow damage

The risk of tree damage by wind (i.e., stem breakage or tree uprooting) following thinning is usually associated with stand age, tree height, the timing of thinning and its intensity (Table 2). By removing a part of the initial stock, thinning immediately lowers stand stability as remaining trees are not accustomed to increasing wind loads, thereby increasing susceptibility to wind and storm damage. The most severe wind damage appears to occur in larger-diameter trees regardless of thinning intensity (Nebeker *et al.,* 2015) and the duration of increased susceptibility is estimated to last from 2 to 10 years after thinning (Pukkala *et al.,* 2016). Detailed scrutiny of broad-scale experiments suggests the risk of wind damage by wind following thinning increases with stand age and tree height (Teste and Lieffers, 2011, Gardiner *et al.,* 2013, Pukkala *et al.,* 2016). According to Gardiner *et al.* (2013), the damage is more extensive in heavy thinning performed in the late stages of the rotation. However, light to moderate thinning may even increase the risk of wind and storms in overly stocked mature stands (Albrecht *et al.,* 2012). Trees in such stands are typically under greater stress with high height-to-diameter ratios and/or low stem taper (Mäkinen and Isomäki, 2004, Saarinen *et al.,* 2020).

However, there is ample evidence to suggest that well-timed pre-commercial or commercial thinning performed at appropriate ages promptly can reduce vulnerability to wind and storm damage. Achim *et al.* (2005) recommended early thinning, particularly on highly fertile sites, to increase wood quality and minimize the risk of wind and storm by promoting the development of structural roots and a more tapered stem. Tarita and Musaka (2020) concurred with the recommendation for a first early thinning followed by an ongoing selection of thinning aimed at the continual release of the crown. According to information from northern Europe, both Norway spruce and Scots pine stands with a mean height of < 10 m are associated with a low incidence of wind damage because of improved development of the root system and increased soil anchorage of the remaining trees (Peltola *et al.,* 1999, Wallentin and Nilsson, 2014). Several studies on Norway spruce or Scots pine in Europe (e.g., Gardiner *et al.,* 2013, Hanewinkel *et al.,* 2014) estimated the period of higher probability of wind damage to range between 2 to 10 years, with heavy thinnings prescribed in the late stages of a rotation (i.e., commercial thinning) leading to the highest increase in risk.

Experiments conducted in recent years reveal sufficient evidence that pre-commercial or commercial light thinning performed at an early stand age can increase stand resistance to the risk of wind and storm damage (Gardiner *et al.,* 2013, Pukkala *et al.,* 2016, Kamimura *et al.,* 2017, Novak *et al.,* 2017, Torita and Masaka, 2020). Beyond the thinning intensity, the method and form of thinning strongly influence stand stability to snow or wind. Thinning from above or below increases the risk of wind damage in Norway spruce, Scott pine and European silver fir (*Abies alba* Mill.) (Albrecht *et al.,* 2012, Pukkala *et al.,* 2016); the risk reduces over time with faster recovery when thinned from below than from above (Moreau *et al.,* 2022). To gain a broader understanding of the underlying processes involved in wind damage following thinning, research has focussed on the development of processed-based models of the interactions between wind and/or snow damage and trees. Duperat *et al.* (2021) described the method of generating balsam fir-specific values of parameters to integrate into the wind risk model Forest GALES, to simulate the impact of different types of commercial thinning on wind damage risk and to determine which practice potentially minimizes the risk in a naturally regenerated stand. The method is based primarily on measuring the wind-induced bending moments experienced in a sample of balsam fir trees by placing an anemometer at canopy height and attaching strain gauges to the trunks. Wind climate parameters for prediction of the probability of damage were calculated using the PC- based airflow model ―Wind Atlas Analysis and Application program (see Troen and Petersen, 1989, Mortensen *et al.,* 2002). The early result of this exercise indicates that thinning from below has a reduced risk of wind damage compared with thinning from above. This and other related concepts (e.g., Blennow and Sallnäs, 2004, Kamimura *et al.,* 2017, Hart *et al.,* 2019) may, however, be explored through further trials and is potential of interest to the silviculture of the most widely regenerated and commercially planted conifer species in Alberta. When thinning from below is performed, the tree with the highest height-to-diameter ratios is removed, and the residual trees reduce their slenderness coefficient, leading to a gain in stability. The subsequent gain in stability may ultimately lead to a reduction of stand vulnerability over the full lifetime of the stand (Zhang and Oliver, 2006, Lundqvist *et al.,* 2007, Wallentin and Nilsson, 2014). In general, the published evidence collectively suggests that in areas where stands are threatened by wind and/or snow loads, it may be necessary to avoid delayed thinning and methods such as thinning from above (dominant thinning) altogether because of the risk.

6.2 Insects and pathogens outbreaks

Thinning may also subject the residual stand to indirect damage from biotic factors such as insects and diseases (Table 3). Pure stands of lodgepole pine are susceptible to infection by stem canker *(Atropellis piniphila* (Weir) Lohman and Cash), blister rusts (*Cronartium* spp.), western gall rust (*Peridermium harknessii*), and *Armillaria* root disease (*Armillaria* spp.). Although cankered stems often render the wood useless for lumber or posts and poles, western gall rust is especially damaging; trunk cankers can cause cull in logs and can kill seedlings and saplings (Mather *et al.,* 2010, Fries *et al.,* 2017). The mountain pine beetle, although historically restricted by climatic conditions (Taylor *et al.,* 2006, Negrón and Huckaby, 2020) is the most severe insect pest of lodgepole pine. In white spruce, spruce beetle (*Dendroctonus rufipennis* (Kirby) has been associated with sites with blowdown, logging slash, or damaged standing timber (Jenkins *et al.,* 2008). Young regenerating sites are very susceptible to Armillaria root rot (*Armillaria mellea*), which causes scattered mortality and windthrow (Westwood *et al.,* 2012).

Results from the Green River study provide evidence that pre-commercial thinning may increase the incidence of butt rot in balsam fir-dominated stands, with incidence proportional to thinning intensity (Warren *et al.,* 2013). They also observed the incidence and volume of butt rot to increase with stem diameter. Cruickshank *et al.* (1997) and Morrison *et al.* (2001) found that the percentage of Douglas-fir trees with *Armillaria* root lesions and subsequent mortality was significantly greater in thinned than unthinned stands in interior British Columbia, but when the same intervention was carried out in ponderosa pine (*Pinus ponderosa*) stands in Central Oregon (Filip *et al.,* 1989, 1999), thinning increased tree diameter growth as well as decreased the incidence of crop-tree mortality after 30 years. Filip and Ganio (2004) later reported results of early thinning of a mixed-species forest of Douglas-fir, Hemlock, and True-Fir; from a root-disease perspective, pre-commercial thinning does not affect the incidence of crop-tree mortality after 20 years. Filip *et al.* (1989, 1999) explained that thinning boosts vigour by reducing competition stress, thereby conceivably enhancing disease resistance among residual host trees. Given this suggestion, the discrepancy between these studies may be in part due to interacting effects (and stresses) associated with climate, such as drought. By further considering the importance of root rot disease in southern pine, it would be of practical value to know whether the overall risk for spreading root rot, given the same periodic mean basal area, is highest with one early heavy thinning or with a more frequent thinning schedule in which smaller amounts of basal area are removed in each thinning (Nebeker *et al.,* 2015). Wang *et al.* (2014) concluded with recommendations for reducing the spread of butt rot in Norway spruce, which supports the view that thinning should occur in winter combined with stump treatment. Though this recommendation from Europe requires some caution as in western North America, *Armillaria s*pore production is at its highest level in January and February. Consequently, thinning during the winter months increases the likelihood of infection because cutting exposes stump surfaces to infection (Nebeker *et al.,* 2015).

Experiments conducted regarding the effects of thinning on gull rust formation are rare in Alberta's forests and any case, are still at too early stage to draw any general conclusion, although a direct relationship between stand age at thinning and stem gall incidences (post-thinning infection) has been identified in western Canada (Blenis and Duncan,1997). Blenis and Duncan (1997) found the incidence of stem gull rust increases as stand density decreases, which supports the view by Anderson and Mistretta (1982) that thinning should be delayed in stands where gull rust is common. One note of caution is that delaying first thinning to such an extent in naturally regenerating lodgepole or white spruce stands may compromise the competitive status of future residual trees (as described by Le Goff and Ottorini, 1996), i.e., the live crown ratio as a proportion of overall tree height and therefore the tree's ability to respond to thinning. Interestingly, when considering both gall rust and root diseases together, thinning has been effective in mitigating the spread of western gall rust (Roach *et al.,* 2015) and improving the overall forest growth of pine affected by *armillaria root disease* (Hood and Kimberley, 2009). In the case of root rot infections of lodgepole pine, the use of chemicals such as borax (sodium borate) or direct stump removal may provide the most positive control of pathogen incidence (Oliva *et al.,* 2010).

Mason (1969) found that thinning attracted large numbers of southern pine engraver (*Ips avulsus* Eichh.) and eastern five-spined engraver (*Ips grandicollis* Eichh.) to infested logging slash in experimental areas. However, the beetles did not attack residual trees and, upon emergence, dispersed to new sources of attraction. Nebeker *et al.* (2005) made similar observations of experimental efforts near Starkville, Mississippi. However, during the following

2 years, some mortality of residual stems occurred when thinning slash was left around the base of residual trees. Despite the negative findings reported by Mason (1969) and Nebeker *et al.* (2005), there is growing evidence that thinning directly reduces the negative effect of different insect outbreaks, such as mountain pine beetles (e.g., Stadelmann *et al.,* 2013; Negrón *et al.,* 2017), sirex woodwasp (*Sirex noctilio*) (Dodds *et al.,* 2014) and spongy moths (*Lymantria dispar* L.) (Fajvan and Gottschalk, 2012).

To summarize, the interactions between thinning treatments and the spread of disease and insects are mixed with thinning often resulting in negative outcomes, though some positive outcomes have been noted across studies. In some instances, mitigation strategies can be used to offset this potential risk. Given the mixed results, the importance of a localized understanding of pathogens is imperative when conducting thinning. Research programs involving PCT and CT should continue to report on outcomes associated with increased or decreased risk of diseases and insects to provide a more comprehensive body of knowledge in this respect.

6.3 Drought resistance

Several studies suggest that a wide range of species and ecosystems are already suffering from drought-related mortality in several parts of their distribution area due to recent warming (Dale *et al.,* 2001., McKenney *et al.,* 2007, Weed *et al.,* 2013). Although drought impacts on forest systems are most severe in water-limited regions, recent trends in elevated tree mortality during changes in the hydrological balance within temperate and boreal ecosystems (e.g., Conly and Van der Kamp, 2001, Vardy *et al.,* 2017) highlight the importance of future drought impacts in northern forests. Lodgepole pine is a ubiquitous species that can grow under a wide variety of climatic and soil conditions (tolerance to minimum temperatures ranges from –7 °C on the Pacific Coast to –57 °C in the northern Rocky Mountains), but it is already suffering from a drought-related decline in several parts of its distribution (Monserud *et al.,* 2008, Liepe *et al.,* 2016). White spruce is less tolerant of drought than lodgepole pine (Nienstaedt and Zasada 1990) and there is also evidence suggesting a decline in the growth of white spruce in western Canada due to recent climatic dryings (Hogg *et al.,* 2017).

A key question related to managing forests within the context of climate change is how to minimize the impacts of increasing drought frequency and intensity. Even if recent work provides incomplete information, there is considerable evidence that thinning treatments have the potential to improve growth and reduce mortality under drought conditions. Water availability in the soil is likely to increase after thinning due to lower interception and consumption through transpiration and thus ameliorating, albeit temporarily, the negative effects of increased drought (Lagergren *et al.,* 2008, Gebhartdt *et al.,* 2014). This positive effect increases with thinning intensity, with heavy thinning that removes more than 40% of the basal area being the most effective (Calev et a., 2016, Zamora-Pereira *et al.,* 2021). Carbon *et al.* (2018) and Bello *et al.* (2019) in an attempt to understand the role of thinning in mitigating climate change removed less than 30% of the basal area and found that such thinning intensity significantly improved radial growth recovery after drought events, but scarcely affected the resistance to drought-induced mortality. In the case of 40% basal area removal, if the crown size is allowed to increase in the case of a single heavy thinning intervention or because of very late and light multiple thinnings then the initial positive effects on drought can even be reversed as the stand matures (D'Amato *et al.,* 2013; Bottero *et al.,* 2021). Such a reversal of positive effect could commence within 20–40 years post-thinning as the leaf/sapwood area ratio increases (D'Amato *et al.,* 2013). A higher leaf/sapwood area ratio in mature large trees often results in increased water demand, which can result in higher vulnerability for thinned stands (D'Amato *et al.,* 2013; Mausolf *et al.,* 2018). Timely intervention may therefore be critical in improving the response and resilience of thinned stands to drought.

7. MODELLING THINNING RESPONSES AND OPPORTUNITIES

7.1 Stand density management diagrams

In terms of managing stand density, Alberta has a long history of treatment protocols guided by a set of large-scale and long-term field experiments as exemplified by the adaptative forest management practices from 1955 to 2005 (Udell *et al.,* 2013). More recently, a range of comprehensive modelling platforms that are essential for forecasting timber supply and supporting silvicultural decision-making to a broad array of density management scenarios, have been advanced. Such examples include individual-tree distance-independent models such as Table Interpolation Program for Stand Yields (TIPSY) and Mixedwood Growth Model (MGM) developed for conifers in western Canada (Di Lucca 1999, Bokalo *et al.,* 2013) and stand-level distance-independent average-tree yield models such as SDMDs (Stand Density Management Diagrams) developed for intensively managed conifers in central and eastern Canada (e.g., Newton, 1993, 2006, 2009, 2012), and the hybrid stand-level distance-independent average tree and size-distribution yield.

Different variations of the stand density management diagram (SDMD) which was introduced to the North American forest science literature by Drew and Flewelling (1977) are being developed as part of industry-based research initiatives. Penner *et al.* (2006) and Swift *et al.* (2007) describe the allometric modelling of density diagrams for balsam fir and spruce–fir mixtures in New Brunswick, which in turn provides some practical silvicultural management guidelines for certain production objectives. The diagrams are based primarily on a maximum size density line, quadratic mean diameter, top height isolines, as well as several mortality functions. Having demonstrated the strong link between mean tree volume, density, and BDH ($r^2 = 0.99$), the models project the rotation lengths required to produce various target harvesting diameters, across a range of mean radial increments and top height. Interestingly, the line of maximum density seems to be also where the maximum spruce budworm mortality occurs in Quebec (Michel Huot, personal communication, November 13, 2022). Farnden (1996, 2002) also provides recommendations for constructing SDMDs for lodgepole pine, white spruce, and Douglas fir in western Canada. Farnden's work presents one of the simplest attempts to model complete rotation for individual conifer species in western Canada since the use of stand yield tables from TASS (Tree and Stand Simulator) and distance-dependent growth models to plot the diagrams eliminated the need to perform complex mathematical analyses of large data sets.

Several zones on these DMDs are useful in making crop plans. For example, maximum individual tree diameter growth occurs just above the crown closure line and maximum volume growth in a unit area, occurs just below the zone of imminent mortality. In between, there is a trade-off between managing for piece size and shorter rotations (value) versus total volume (Figure 1). Rotation ages to produce merchantable timber can be shortened by managing stand density to favour increased individual tree diameter, however, in very aggressive commercial thinnings there will be a reduction in total stand volume produced. Crop planning begins with the manager deciding on what desired stand conditions should exist at the final harvest, concerning piece size and stand density. From there the DMD and growth models can be used to work backwards to predict the optimum stand conditions, timing, and amount to remove in pre-commercial and commercial treatments, considering species silvics and economics.

In DMDs, there are three principal model variants: (1) 2-dimensional (size-density) static SDMDs (Drew and Flewelling, 1979), (2) 3-dimensional (size density-time) dynamic SDMDs (Stankova and Shibuy, 2007), and (3) n-dimensional (size-density-time-distributional) structural SDMDs (Stankova and Diéguez-Aranda, 2020). More generally, the hierarchical-based structural SDMD modelling framework may contain several sequentially linked estimation modules for predicting the optimum stand condition. Module A—Dynamic SDMD— integrates a broad array of the static and dynamic yield–density relationships most of which are graphically presented within the traditional SDMD graphic; Module B—Diameter and Height Recovery—embeds a stand-type-specific (1) parameter prediction equation system for diameter distribution recovery. Cao (2004) parameterized using the cumulative density function regression approach. Module C—Taper Analysis and Log Estimation—deploys species-specific nonlinear dimensional-compatible taper equations. Examples are the functions developed for jack pine and black spruce by Sharma and Zhang (2004) and Sharma and Parton (2009). Module D—Biomass and Carbon Estimation—uses species-specific composite multivariate allometric-based biomass equations from which the above-ground total and component (bark, stem, branch, and foliage) biomass and associated carbon-based equivalent mass estimates, are generated at the individual tree level and subsequently scaled to the diameter-class and stand levels. An example includes Newton's equations (2006) for black spruce and Newton's equations (2009) for jack pine). Module E—Product and Value Estimation—utilizes species and sawmill-specific product and value equations to predict diameter-class and stand-level estimates of recoverable volumes of chip and lumber products along with their associated monetary worth values. A typical example includes the one derived from the Optitek sawing simulator output (Liu and Zhang, 2005, Newton, 2009), Module F—Fibre Attribute Estimation—employs either a species-specific composite function for estimating mean whole-stem wood density and mean maximum branch diameter or a hierarchical mixed-effects prediction model (Newton, 2016) for estimating rotational end-product (e.g., wood density, microfibril angle, modulus of elasticity, fibre coarseness, tracheid wall thickness, tracheid radial diameter, tracheid tangential diameter and specific surface area values at breast-height (1.3 m) stem position). From here, the SDMD and growth models can be used to work backwards to predict the optimum stand conditions, timing, and amount to remove in pre-commercial and commercial thinning treatments. Such growth models include (1) individual-tree distance-independent models such as TIPSY (Table Interpolation Program for Stand Yields), TASS (Tree and Stand Simulator), and MGM (Mixedwood Growth Model) developed for conifers in western Canada [Bokalo *et al.,* 2013], (2) stand-level distance-independent average-tree yield models such as SDMDs (Stand Density Management Diagrams) developed for intensively managed conifers in central and eastern Canada (e.g., [Newton and Weetman, 1993, Sharma and Zhan, 2007]), and (3) hybrid stand-level distance-independent average tree and size-distribution yield models such as SSDMDs (Structural SDMDs) developed for boreal conifers in central Canada (Newton, 2009, 2012).

7.2 Opportunities for advancing SDMDs to provide management guidelines

Despite the high acceptance of SDMD as one of the preferred density management decision-support platforms, there are still opportunities for improvement. This could involve the introduction of a spatial distribution metric to account for the transition from a clustered to a uniform-like spatial pattern that commonly occurs when a natural-origin stand undergoes pre-commercial thinning. Newton (2006) provided guidelines for stand-level forest production and carbon budgeting decision-support model for natural-origin black spruce stands which included the expansion of the SDMD by adding allometric equations for predicting biotic component masses (e.g., bark, stem, branch, foliage, and fine and coarse roots) and abiotic component masses (e.g., needle loss, root turnover, abscised modular components, and coarse wood debris arising from self-thinning) at any point along a given size–density trajectory. Potential increases in productivity arising from increased carbon dioxide concentrations (CO_2 fertilization effect) have not yet been quantified and incorporated into SDMDs. However, the effect of climate change could, in principle, be accounted for within the SDMD analytical structure by adding sub-models that explicitly account for species' genetic worth through modification to the site-specific height–age equations (Newton 2015, 2016).

To-date, the lack of sufficient data to develop and validate plausible stand-wide solutions to these analytical challenges has largely negated SDMDs resolution to date. For example, stands with reduced crown dimensions are at risk of 'thinning shock' or a delayed response to thinning treatments. Information is needed on how crown attributes such as live crown ratio, crown volume/bulk density, leaf area index, etc. are related to thinning response. These may be variables that are not easily measured using traditional methods. Consequently, until these issues are resolved possibly through innovations like LiDAR and other geospatial information sources (Moss 2012; Koch *et al.,* 2006), fine-scaling differentiation of several key stand attributes among competing treatment regimes will be limited.

8. CONCLUDING REMARKS

In general, the literature compiled in this review has revealed sufficient evidence to support the view that stands density management through thinning is likely to have positive effects on tree growth, although the magnitude depends on the thinning regime, the region, site, and stand age. Heavy thinning (removing more than 40% of basal area) can be effective at maximizing the diameter increment of future crop trees and may provide short-term mitigation of drought conditions. However, if not performed at an early stage, moderate to heavy thinning can destabilize stands and cause wood volume losses by increasing vulnerability to wind and storm damage. This higher vulnerability can last from 2 to 10 years following thinning. Numerous studies recommend thinning lodgepole pine stands to a basal area of approximately 18 square meters of basal area per hectare to reduce both the frequency and intensity of mountain pine beetle infestations, though heavy thinning may not be universally appropriate because of other more certain risks and losses. Light thinning (removing no more than 25% of the stand's basal area) can be an effective tool for resisting insect and pathogen outbreaks. In case of a significant insect outbreak, light and repeated thinning treatments could have a positive legacy effect on shaping post-outbreak successional trajectories. Regarding pathogen infections such as *Armillaria* root disease, contemporary stump treatment may be necessary to avoid the spread of infection in stands where this disease is prevalent. Thinning part of the stand temporarily increases the risk of wind damage to residual trees. Because the risk of wind damage through thinning increases with stand age and height, it is recommended that delayed heavy thinning should be avoided in mature stands where the risk of wind damage is high.

Forest managers cannot be expected to maximize all ecosystem services and functions at the same time, so it is crucial to have a solid understanding of the key motivations and objectives behind a thinning program and to identify trade-offs or limitations that may arise as a consequence. Besides the typical trade-offs between wood yield and value, thinning can involve other trade-offs such as those between wood yield or quality and factors causing indirect thinning damage including wind, ice, and the possibility of increased incidence of insects and disease, which need to be accounted for. Trade-offs between adaptation to and mitigation of climate change impacts such as drought are especially important for thinning interventions. To adapt lodgepole pine or white spruce to the severity of drought (predicted for many regions in Alberta), some of the research identified suggests that heavy thinning may provide some respite to remaining trees; however, the upper limit for effective high-intensity thinning as well as the timeframe that this benefit may be realized remains uncertain.

While this review mainly investigated the potential of thinning in these contexts from North American and European perspectives, studies from Alberta's boreal forests are drastically underrepresented, with few rigorous experiments highlighting what influences density-independent mortality following thinning. It is therefore not surprising that forest managers in the province currently lack strong evidence to identify interventions that maximize volumetric yields, end-product quality, and value without compromising the forest's resilience against multifaceted and unexpected risks in the future. For thinning to become part of normal forestry operations in Alberta, a first step should be to revisit the existing trials and studies, to link key stand attributes, such as density, structure, and composition to thinning prescriptions and stressors and their interactions (Moreau *et al.,* 2022). In parallel, there is an imperative for new thinning trials that include a variety of thinning treatments, to identify key stand attributes that can be linked with resistance and resilience to future forest stressors. Future thinning treatment trials in Alberta need to be located across a broad range of stand types in natural or managed stands, representing a continuum of homogenous (single species) to heterogeneous (mixed-species and strata) blocks. This would facilitate the full replication of a broader range of treatments; future focus on heterogeneous stands and potentially integrating reforestation practices to encourage more of these stand types is likely a wise step forward from a risk-mitigation standpoint. Multi-species stands may include multiple coniferous species plantings as well as mixed wood stands.

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10. LIST OF TABLES

Table 1. Summary of long-term lodgepole pine stand thinning and fertilization trial trials in Alberta in this review

Trial name	Author(s)	Thinning treatment/ Age at thinning	Species**	Thinning regime		Data collection	Target variable	Effects*
				Basal area removed	Method			
K-57	Quaite 1950 Stewart *et al.* 2006	Commercial 77 years	Lodgepole pine	66% (heavy intensity)	Above +below	22 years	Total Volume growth	—
							Merchantable volume	—
							Mean height	—
							Basal area (BA)	—
							Quadratic mean diameter	ǂ
							Mean DBH	ǂ
							Slenderness (ht/dbh)	—
							Spacing factor (SF%)	ǂ
						58 years	Total Volume growth	ǂ
							Merchantable volume	ǂ
							Mean height	ǂ
							Basal area (BA)	ǂ
							Quadratic mean diameter	ǂ
							Mean DBH	ǂ
							Slenderness (ht/dbh)	—
							Spacing factor (SF%)	ǂ
MacKay	Smithers 1961 Stewart *et al.* 2006	Pre-commercial 22 years	Lodgepole pine	64-76%; two thinning entries at 22 and 37 years	Future crop tree (selective)	49 years	Total Volume growth	—
							Merchantable volume	ǂ
							Mean height	ǂ
							Basal area (BA)	—
							Mean DBH	ǂ
							Slenderness (ht/dbh)	0
Strachan	Crossley 1955 Stewart *et al.* 2006	Pre-commercial 85 years	Lodgepole pine	50% (heavy)	Below	54 years	Total Volume growth	—
							Merchantable volume	—
							Mean height	—
							Basal area (BA)	ǂ
							Mean DBH	0
					Above (crown)		Total Volume growth	—
							Merchantable volume	—
							Mean height	—
							Basal area (BA)	ǂ
							Mean DBH	—
					Sanitation*** cut		Total Volume growth	—
							Merchantable volume	—
							Mean height	—
							Basal area (BA)	ǂ
							Mean DBH	—

Table 1. Cont'd.

Trial name	Author(s)	Thinning treatment/ Age at thinning	Species**	Thinning regime		Data collection (post-treatment)	Target variable	Effects*
				Basal area removed	Method			
Swan Lake	Bella 1990 Stewart *et al.* 2006	Pre-commercial 9 years	Lodgepole pine	>80% (heavy)	Below	26 years	Total Volume growth	—
							Merchantable volume	ǂ
							Mean height	ǂ
							Basal area (BA)	—
							Mean DBH	ǂ
							Slenderness (ht/dbh)	0
Gregg Burn	Stewart *et al.* 2006	Pre-commercial 7 years	Lodgepole pine	>50% (heavy)	Below	36 years	Total Volume growth	0
							Merchantable volume	ǂ
							Mean height	ǂ
							Basal area (BA)	0
							Mean DBH	ǂ
							Slenderness (ht/dbh)	0
Ricinus Thinning+Fertilization	Stewart *et al.* 2006	Pre-commercial 15 years	Lodgepole pine	>80% (heavy)	Below	39 years	Total Volume growth	—
							Merchantable volume	—
							Mean height	0
							Basal area (BA)	0
							Mean DBH	0
							Slenderness (ht/dbh)	0
McCardell Creek Road Thinning+Fertilization	Stewart *et al.* 2006	Commercial 40 years	Lodgepole pine	>50% (heavy)	Below	20 years	Total Volume growth	—
							Merchantable volume	—
							Mean height	0
							Basal area (BA)	ǂ
							Mean DBH	0
Takyi Thinning+fertilization	Stewart *et al.* 2006	Pre-commercial 24 years	Lodgepole pine	75% (heavy)	Below	19 years	Total Volume growth	—
							Merchantable volume	ǂ
							Mean height	ǂ
							Basal area (BA)	ǂ
							Mean DBH	ǂ
							Slenderness (ht/dbh)	0

Table 1. Cont'd

Trial name	Author(s)	Thinning	Species**	Thinning regime		Data collection	Target variable	Effects*
		Age at thinning		Basal area removed	Method			
Takyi Thinning+fertilization	Stewart *et al.* 2006	Pre-commercial 24 years	Lodgepole pine	75%	Future crop tree (selective)		Total Volume growth	—
							Merchantable volume	ǂ
							Mean height	ǂ
							Basal area (BA)	ǂ
							Mean DBH	ǂ
							Slenderness (ht/dbh)	0

*Positive and negative effects are indicated by + and -, respectively; 0 indicates no effect; ** Stands were of fire origin; *** The sanitation cut did not consider final density or spacing; instead, trees with a diameter at breast height of over 7.6 cm that was badly suppressed, diseased, or deformed, such that they would be unmerchantable as poles or pilings at final harvest, were all removed.

Table 2. Summary of the effect of thinning treatments on wind damage risk

Author	Biome (Country)	Species	Thinning treatment (entries)	Basal area removed	Risk of wind damage short-term	 long-term	Remark
Achim *et al.* 2005	Boreal (Canada)	Balsam fir	Pre-commercial (1) + Commercial (1)	30%		—	The wind speed increased with a reduced stand density
Novak *et al.* (2017)	Temperate (Czech Republic)	Norway spruce	Commercial -below and above (2)	20%, 60%	—		Tree mortality was reduced 25 years after treatment
Duperat *et al.* 92021)	Boreal (Canada)	Balsam fir	Pre-commercial (1) + Commercial - below and above		0/+		Thinning from above decreased critical wind speed
Pukkala *et al.* (2016)	Boreal (Finland)	Norway spruce	Pre-commercial + Commercial - below and above (3-40	Variable	+	—	Thinning from above increased tree vulnerability to wind damage; negative effect decreased with time
Hanewinkel *et al.* (2014)	Temperate (Switzerland)	Norway spruce	Commercial	Variable	0/-		No effect of thinning intensity; wind damage decreased with time since thinning (measured up to 8 years)
Gardiner *et al.* (2013)	Europe*	Several conifers	Pre-commercial; Commercial		+/—	—	Late heavy thinning increased wind vulnerability Pre-commercial thinning increased ?? wind resistance 5-10 years after thinning
Albrecht *et al.* (2012)	Temperate (Germany)	Norway spruce Douglas fir	Commercial -above and below	50%	+		Heavy thinning from above-destabilized stand
Bigelow *et al.* (2021)	Temperate (USA)	Pine-broadleaf mix	Commercial		—		Only marginal effect
<u>Ruel *et al.* (2001)</u>	Boreal (Canada)	Balsam fir Black spruce White spruce	Commercial–above	35,64%	0/—		No effect of thinning method; risk decreased with time since thinning (measured up to 9 years)
Valinger and Pettersson (1996)	Boreal (Sweden)	Norway spruce Scott pine	Commercial–below and above	20%,70%	+		Thinning from above or below destabilized stands; higher wind mortality in thinned stands than unthinned stand

Positive and negative effects are indicated by + and -, respectively; 0 indicates no effect; empty cells represent non-available information.

Table 3. Overviwed of published evidence on the effects of thinning treatments on insect and pathogens infestation (assessed through percentage of trees attacked following thinning and mortality.

Author	Biome (Country)	Species	Insect/ Pathogen	Thinning treatment (entries)	Basal area removed	Effect		Remark
						% Attacked	Mortality	
Filip *et al.* (1999)	Temperate (USA)	Douglas fir	Armillaria root disease	Pre-commercial -below	10%		–	Positive effect on reducing root disease
Hood and Sala (2016)	Temperate (USA)	Douglas fir Ponderosa pine	Bark beetle	Commercial–below (1)	0, 50-60%		0/–	Heavy thinning was not effective
Scheller *et al.* (2018)	Temperate (USA)	White fir	Bark beetle	Commercial–below + prescribed burning (1)			0/–	Positive effect on reducing tree mortality; ineffective at the landscape scale
Stadelmann *et al.* (2013)	Temperate (Switzerland)	Norway spruce	Bark beetle	Sanitation cut (1)			¥/–	Windstorm increased bark beetle infestation
Negrón *et al.* (2017)	Temperate (USA)	Ponderosa pine	Mountain pine beetle	Commercial–below (1)			–	Thinning from below was most effective
Steel *et al.* (2021)	Temperate (USA)	White fir	???	Commercial–below and above + commercial burning (1)	variable	+/–	0/–	Thinning + burning increased beetle infestation probability
Regolini *et al.* (2014)	Temperate (France)	Maritime pine	Root and but rot	Commercial–below +stump treatment	0, 33, 50%	0	–	Complementary stump chemical showed great potential to reduce root rot infection
Six *et al.* (2014)	Temperate (USA)	???	Mountain pine beetle	Commercial			0/–	Commercial thinning performed at an early stand age generally reduces mortality
Morris *et al.* (2022)	Temperate (USA)	Lodgepole pine	Mountain pine beetle	Commercial	variable			Only marginal effect on resistance

Positive and negative effects are indicated by + and -, respectively; 0 indicates no effect; empty cells represent non-available information

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Figure 1. Demonstration of the trade-off between value and volume using an example of TASS runs for Douglas-fir with a harvest age of 60 years (from BC Ministry of Forests 1999). Note the highest volume is produced when thinning to 600 to 800 tph, yet the highest value (NPV) occurs at a residual density of 200 tph.