Mid-Rotation Thinning Strategies in Lodgepole Pine Under Varying Stand Density Conditions: A TASS Simulation Study

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Abstract

Stand density is a primary driver of structure, growth, and productivity in even-aged lodgepole pine (*Pinus contorta var. latifolia*) stands. This study evaluated responses across three mid-rotation lodgepole pine blocks using stand-level metrics and TASS growth modeling. Species-level analyses showed that lodgepole pine dominated all blocks, accounting for 74–95% of stand composition and exhibiting low variability across basal area, diameter, and stem density (CV ≤ 20%). In contrast, spruce, balsam fir, and deciduous species displayed high coefficients of variation (57–118%) which shows little contribution to stand structure or dynamics. Low Shannon diversity and evenness values further confirmed the monoculture nature of these stands. This supported the exclusion of minor species from growth modeling and the treatment of each block as a lodgepole pine monoculture in TASS simulations.

When modeling thinning scenarios, the responses differed greatly depending on initial stocking level. In the overstocked block, thinning reduced early density driven mortality, increased diameter growth, and improved total volume by capturing stems otherwise lost to self-thinning. In the moderately stocked block, thinning increased individual tree size but reduced total yield. This showed that thinning timing is more critical than thinning intensity. In the understocked block, thinning provided minimal structural benefit and resulted in substantial volume loss. Results suggested that thinning is counterproductive when stands are below the Zone of Imminent Mortality (ZIM).

Overall, results indicate that optimal management of lodgepole pine stands depends on maintaining mid-rotation stem densities near 900–1200 stems per hectare. This allows for the highest productivity by to minimizing mortality and maximize yield. Thinning is most beneficial in overstocked stands, due to competition induced mortality. Moderately stocked stands require delayed thinnings to fully take advantage of the treatment. While thinning is not recommended in understocked stands. This study emphasizes the importance of early density management and site-specific silvicultural prescriptions to optimize long-term stand productivity.

Problem Definition

The forestry industry in British Columbia has been harvesting timber since the early 1900s. BC is covered by around 57-59 million hectares of forest and produces more timber than any other province in Canada (Kooten et al. 2019). The forestry sector is a massive backbone of the BC job market. For instance, 1 in 28 people work in the industry, supporting 100,000 jobs across the province (Cofi 2024). Regions like the Cariboo have 22% of its workforce in the industry. The forestry industry provides huge economic benefits for the province. Lumber accounts for 24% of BC's exports, with the industry bringing in $17.4 billion to the BC GDP in 2024 (Cofi 2024). With such a large population being dependent on forestry in BC and less than 0.4% of forested area harvested annually, the sustainability of forests in BC is a necessity.

The forestry industry in British Columbia has been harvesting timber since the early 1900s, and the effects of this long-standing resource extraction continue to shape the landscape today. Pre- and post-harvest management decisions dictate how the future forest structure will be. Pre-commercial thinning (PCT) and commercial thinning (CT) are management options to improve both stand structure and productivity (BC Ministry of Forests, 2025). Understanding how these treatments affect stand structure over time is essential for assessing the current state of forest resources. By modeling the effects different thinning treatments have on multiple stand densities, this study aims to better understand how initial stand density and commercial thinning intensity influence mid-rotation stand development in lodgepole pine.

Background

A Shift in Forest Management in BC

A silviculture system refers to the process of developing, maintaining, and replacing a forest stand over time through intentional management interventions (Bettinger et al., 2017). The

intensity and developmental pathway of these interventions can vary, leading to different stand structures and outcomes. To design and implement effective, site-specific silviculture plans, clearly defined targets and objectives are required. Prescribed treatments within these systems may include harvesting, regeneration (through planting or natural regeneration), thinning, intermediate cuttings, and stand tending (Bettinger et al., 2017).

In British Columbia, clearcutting followed by the establishment of a single-age class stand remains the most applied silviculture system due to its economic efficiency (Bettinger et al., 2017). However, there is a growing shift toward adopting a wider range of silvicultural systems aimed at achieving diverse ecological and social objectives beyond purely economic considerations. Traditional forest management in BC historically focused on maximizing timber productivity, often promoting even-aged stands through clearcutting and replanting of commercially viable conifer species (Parsons 2003). In recent decades, forest management has begun to prioritize resilience and sustainability, shifting from production-oriented systems to practices that retain more canopy cover and lengthen harvest rotations (Wang 2024). Using PCT and CT practices to manage for long term lodgepole pine productivity is an example of this shift in management (Hossain, 2022).

Lodgepole Pine

Lodgepole pine (*Pinus contorta var. latifolia*) is a pioneer species that plays a dominant role in the Sub-Boreal Spruce zone of northern British Columbia. As a fire adapted species with serotinous cones, it regenerates in high densities following major disturbances such as fire or clearcutting (Rweyongeza et al,. 2010). For this reason, clearcut systems are often used to mimic natural disturbance patterns and promote pine regeneration. Following harvest or fire, lodgepole pine typically establishes at very high densities. This can lead to overcrowding, increased competition, reduced resource availability all resulting in suppressed growth (Johnson, et al,. 1989).

To address these challenges, pre-commercial thinning (PCT) and commercial thinning (CT) have proven effective in reducing stem density and improving stand development (Hossain, et al,. 2022). By lowering competition, trees gain increased canopy space and resource

availability. This allows for continued diameter growth while preventing stagnation typically present in overcrowded stands (Hossain, et al,. 2022). These thinning practices are designed to concentrate growth on a smaller number of stems, thereby improving overall stand productivity.

Pine species have demonstrated significant economic benefits from intensive silvicultural practices. Studies of managed pine stands in British Columbia have shown that such approaches can significantly impact tree growth and maximize productivity of slow growing stands (Danyagri, et al,. 2023). These practices are especially important given that lodgepole pine stands often grow on nutrient poor soils following fire. These disturbances reduce soil nitrogen content, leading to productivity constraints in subsequent rotations (Johnson, et al,. 1989). To mitigate this fertilization has been applied in some management systems to enhance stand growth and sustainability. Commercial thinning has widely been adopted in around the world but has yet to be fully implemented within silviculture operations in BC. Due to CT being costly and requiring significant management there is currently no path forward to widescale implementation (Hossain, et al,. 2022).

Commercial thinning in lodgepole pine stands

The goal of commercial thinning is to maintain reasonable growth rates of remaining trees by reducing stand competition. In doing so, thinning provides access to supplementary fiber that would otherwise be unavailable until end of rotation harvests (Hossain, et al,. 2022). Thinning can also influence disturbance dynamics by reducing drought stress, limit the spread of pests, and decreasing fuel load and ignition potential for wildfire (Danyagri, et al,. 2023).

In British Columbia, thinning practices are guided by the provincial manual *Thinning Guidance in BC*. The manual identifies several key effects of thinning which support stand productivity, resilience, and long-term management objectives.

Thinning improves stand condition by removing dead, dying, or diseased trees while retaining healthier stems (BC Ministry of Forests, 2025). Trees with structural defects, such as broken tops or poor form, are typically removed first to enhance overall stand vigor. Thinning also supports ecosystem resilience by reducing competition for light, water, and nutrients (BC

Ministry of Forests, 2025). By reducing stand density forest resources can be focused on fewer larger stems thus improving the overall health of the ecosystem. In addition to this thinning removes densely packed stems which allows for a lowering fuel accumulation and a reduced ignition risk (BC Ministry of Forests, 2025).

From an economic and operational perspective, thinning promotes innovation and enhances fiber utilization. By creating new markets for small diameter or non-traditional fibers, thinning offers alternative fiber products usually unattainable in fully mature stands (BC Ministry of Forests, 2025). Concentrating site resources into fewer residual stems improves both operational and site-specific efficiency by increasing individual tree growth and value. Furthermore, by reducing fire risk, associated suppression costs are lowered. Thinning enhances economic value by supplying fiber to facilities by producing a broader range of log sizes (BC Ministry of Forests, 2025).

Finally, thinning retains sufficient residual stocking to meet stand development objectives. This is achieved by minimizing the width of trails and gaps while retaining trees with adequate live crown ratios. In addition to maintaining wind firmness through appropriate block design and stable height-to-diameter ratios the goal is to achieve the target post-thinning residual stocking density (BC Ministry of Forests, 2025).

Overall commercial thinning seeks to improve the productivity of the forest while maintaining structure and improving forest resilience. Understanding the management pathways which enable this is crucial to reaching target objectives.

Rationale

Lodgepole pine management outcomes are highly dependent on the interaction between thinning treatments and stand density. Understanding this interaction is essential for guiding thinning strategies to maximize productivity and promote overall forest health.

Purpose Statement

The purpose of this study is to evaluate lodgepole pine (*Pinus contorta var. latifolia*) management in commercial thinning blocks. By modeling the effects of thinning treatments on different mid-rotation stand densities, this study aims to inform management strategies for maintaining productive and resilient lodgepole pine forests.

Project Objectives

Primary Objective:

To evaluate how initial stand density and commercial thinning intensity influence mid-rotation stand development in lodgepole pine.

Sub-Objectives:

1. **Identify and characterize harvest history:** Using aerial imagery and records to determine the timing and harvesting practices in the study blocks.
2. **Assess mid rotation stand structure**: Using current timber cruising data (height, DBH, volume, stem density and species composition) for stands 40 years of age.
3. **Compare stand-level responses to thinning across three stand densities:** Overstocked, moderately stocked, and understocked.
4. **Assess how thinning intensities affect growth and productivity of the stands:** at 18%, 25% and 35% BA removed.
5. **Provide management direction for thinning treatments of sampled blocks.**

Methods

Determining Harvest Year Using Aerial Imagery

The approximate harvest year for each study block was identified through the analysis of historical aerial imagery. Images from multiple years were examined to detect the transition from mature forest to recently harvested conditions. The first appearance of exposed soil and logging disturbance was seen around 1985, thus stand initiation occurred after this date. This timing allowed reconstruction of stand age at the beginning of the TASS simulations and verified that all study blocks were mid-rotation at approximately 40 years of age.

Initial Stand Analysis and Rationale for Stand Selection

Before selecting the three study blocks for detailed modelling, all blocks were evaluated to determine structural differences and ensure that the chosen blocks represented distinct stand conditions.

Metrics analyzed included:

- stems per hectare,
- average DBH,
- total height,
- basal area,
- and merchantable volume.

A one-way ANOVA was performed on these variables. Significant differences were found in stem density and average DBH among blocks. This indicated a meaningful structural variation in mid-rotation stand development.

Further a Pearsons correlation test was run on stems per hectare and average DBH that indicated a significant negative correlation of stem density to DBH. Based on

these differences, blocks 1, 6, and 8 were selected to represent a clear density gradient across overstocked, moderate and sparsely stocked stands. This provided an appropriate framework for evaluating thinning response under contrasting stand conditions.

Study Stands and Cruise Data

Cruise data for each block included stems per hectare, species composition, average DBH, height, basal area, and merchantable volume. Blocks were classified based on observed initial stem density:

- **Block 1** – Overstocked (~1650 stems/ha)
- **Block 6** – Moderately stocked (~1214 stems/ha)
- **Block 8** – Understocked (~845 stems/ha)

These initial conditions provided contrasting stand structures, enabling assessment of how thinning intensity interacts with existing density.

Stand Reconstruction and TASS Stem-List Generation

TASS simulations require individual tree input files containing species, DBH, height, and age. Stand-specific stem lists were constructed as follows:

1. Tree count determination: stems per hectare were converted into number of simulated trees using the TASS convention of 1 tree representing 4 m^2.
2. DBH distribution: values were sampled from cruising data to generate sample list.
3. Height estimation: heights were centered around cruise average height.
4. Age assignment: all trees were assigned an initial age of 40 years.
5. File formatting: each stem was written to a .txt file in the required four column format:

Species | DBH | Height | Age

This process produced realistic stand structures matching those seen in collected cruising data.

TASS Growth Simulations

All simulations were run using TASS v3, projecting stand development from 40 to 80 (earliest harvestable age for LP). Growth assumptions, site index, and mortality functions remained constant across all runs.

Four management treatments were simulated for each block:

1. Un-thinned (Control)
2. Scenario A – Light thinning (18% basal area removal)
3. Scenario B – Moderate thinning (25% basal area removal)
4. Scenario C – Heavy thinning (35% basal area removal)

Thinning occurred at year 40, immediately following the baseline stand condition. TASS performed an attribute thinning based on percentage of basal area, primarily removing smallest DBH trees first. No natural regeneration was included, as stands were mid-rotation and treatments were designed to test thinning effects on existing growing stock.

Stand Metrics Extracted

Annual outputs were extracted for four primary metrics:

- Basal Area (m^2/ha)
- Mean DBH (cm)
- Stems per hectare (stems/ha)
- Total volume (m^3/ha)
- Natural mortality (natural loss of stems/ha)

Three focus years were identified: Initial (age 40), post treatment (age 41) and mature (age 80).

Mortality and Thinning Quantification

Natural mortality was assessed by analysis stems/ha loss and mortality outputs via the TASS model. Thinning removals for each treatment was calculated as the additional reduction in stems/ha relative to the mortality in each stand.

Statistical Analysis

The initial stand comparison (ANOVA) established that Blocks 1, 6, and 8 represented meaningfully different density conditions. No inferential statistics were applied to TASS outputs, as the model is deterministic. Comparisons among scenarios were made using descriptive trends.

Graphical Analysis

Time series graphs were generated for each metric (BA, DBH, stems/ha, volume) from age 40 to 80. Trends were compared across thinning intensities for each block to evaluate:

- immediate response to thinning,
- long-term recovery,
- stand development trajectories,
- and final stand condition.

Software Tools

Data handling, calculations, and figure creation were performed in **R** using tidy verse, dplyr, and ggplot2. TASS modelling was conducted using the TASS v3 GUI environment.

Results

Variation between blocks

Table 1. One-way ANOVA results for differences in stand density, tree size, volume, and height among sampled blocks.

Metric	F-value	p-value	Significance Interpretation
stems/ha	**23.67**	**0.0046**	**Significant — strong difference between blocks**
Average DBH	**10.02**	**0.025**	**Significant — tree size differs between blocks**
Net Merchantable Volume	**4.20**	**0.0958**	**Not significant — (p < .10) possible emerging difference**
Basal Area (Ba/ha)	**1.57**	**0.266**	**Not significant**
Total Height	**2.96**	**0.146**	**Not significant**

Significant = p < 0.05, Not significant = p > 0.05

A one-way ANOVA revealed significant differences among the seven sampled blocks for stems per hectare (F = 23.67, p = 0.0046) and average DBH (F = 10.02, p = 0.025). Net merchantable volume showed a marginal, non-significant trend (F = 4.20, p = 0.0958), while basal area (F = 1.57, p = 0.266) and total height (F = 2.96, p = 0.146) did not differ significantly among blocks.

Species composition

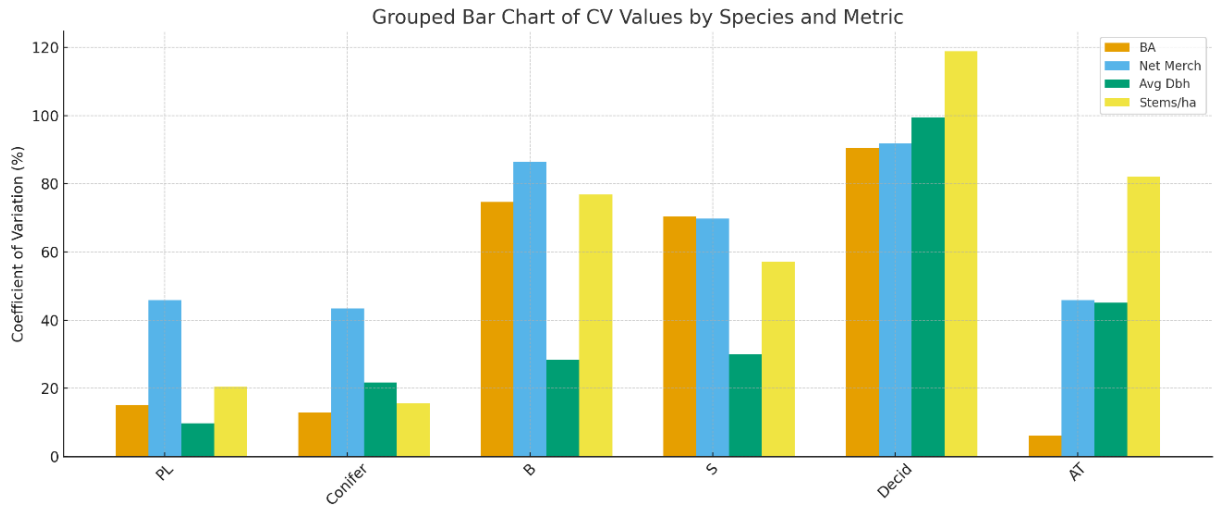

Figure 1Coefficient of variation (CV) values for basal area, net merchantable volume, average DBH, and stems per hectare across species groups.

Species-level variability analysis showed clear differences in how individual species contribute to stand structure across the seven blocks. Lodgepole pine (PL) was the most consistent and dominant species across all seven blocks. This reflects the monoculture nature of these managed stands. Basal area (CV = 15.10%) and stems per hectare (CV = 20.41%) showed low variability. While average DBH was the most consistent between the blocks (CV = 9.76%). This shows that in both structure and density pine is the most stable species.

In contrast, balsam fir (B) and spruce (S) showed substantially higher variation across all metrics. Balsam fir exhibited high variability in basal area (CV = 74.6%) and stems per hectare (CV = 76.8%), as well as large fluctuations in merchantable volume (CV = 86.4%). Spruce showed similar high variability across the blocks, with CV values of 70.3% for basal area, 69.8% for volume, and 57.1% for stems per hectare. Deciduous species were the most variable group overall. Their basal area CV was extremely high (90.4%), and stems per hectare showed similarly large dispersion (118.8%).

Minor species such as Cottonwood (AC), Aspen (AT), and Douglas fir (F) were extremely inconsistent between the blocks. Cottonwood and Douglas fir were only present in one block each, meaning CV calculations could not be performed. Aspen occurred in two blocks although only contributing to ~3% of the total species distribution in each block. These species sparse and inconsistent occurrence suggests they play no significant role in current stand structure or future yield projections.

Shannon diversity index

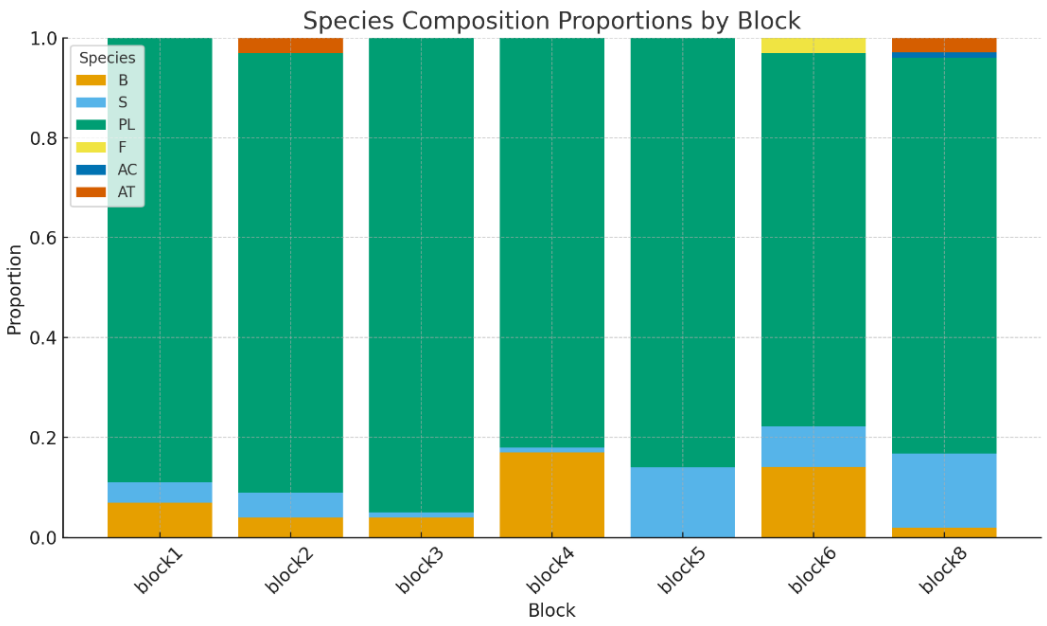

Figure 2 Species composition proportions by block.

Table 2 Shannon diversity, species richness, and evenness indices by block.

Block	**H' (Shannon)**	**Richness (R)**	**Evenness (J')**	**Key Interpretation**
block 1	0.419	3	0.381	Low diversity, strongly pine-dominated
block 2	0.496	4	0.358	Slightly more diverse but still pine-dominant
block 3	0.224	3	0.203	Very low diversity, near-monoculture pine
block 4	0.510	3	0.464	Moderate diversity but pine still dominant
block 5	0.405	2	0.584	Very low richness; only PL + S
block 6	0.803	4	0.580	Highest diversity (F appears), still pine-led
block 8	0.696	5	0.432	Most species present but pine still overwhelmingly dominant

Shannon values: **< 1.0** = very low diversity, **1–2** = moderate, **> 2** = high complexity

Shannon diversity values ranged from H' = 0.22 to 0.80 across all blocks, indicating very low species diversity consistent with early- to mid-rotation lodgepole pine stands. Species richness ranged from 2 to 5 species per block consistent with minimal species variation between blocks. Pielou evenness values (J' = 0.20–0.58) showed that species contribution was uneven. In all blocks, lodgepole pine accounted for 74–95% of total stand composition. The uneven distribution is due to the high variability of other species across the blocks

Pearson's correlation between metrics of lodgepole pine across blocks

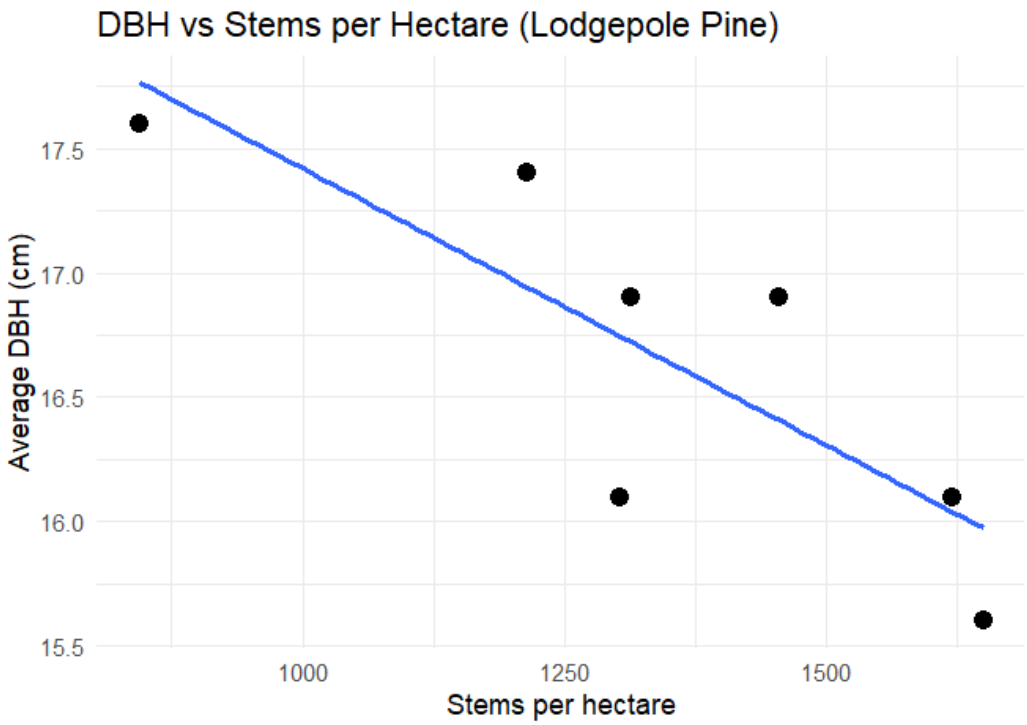

Figure 3 Relationship between average DBH and stems per hectare for lodgepole pine.

DBH vs stems/ha: r ≈ –0.82, p ≈ 0.023

Correlation analysis of lodgepole pine structural attributes across the seven blocks revealed strong density-related patterns. Mean DBH and stems per hectare show a significant and strong negative correlation (r = –0.82, p = 0.023). This indicates that areas which have a higher number of stems have a lower DBH. Higher pine density creates high competition which

actively constrains diameter growth. We see the opposite is true as well. The highest mean DBH was recorded in the blocks with the least stems per hectare.

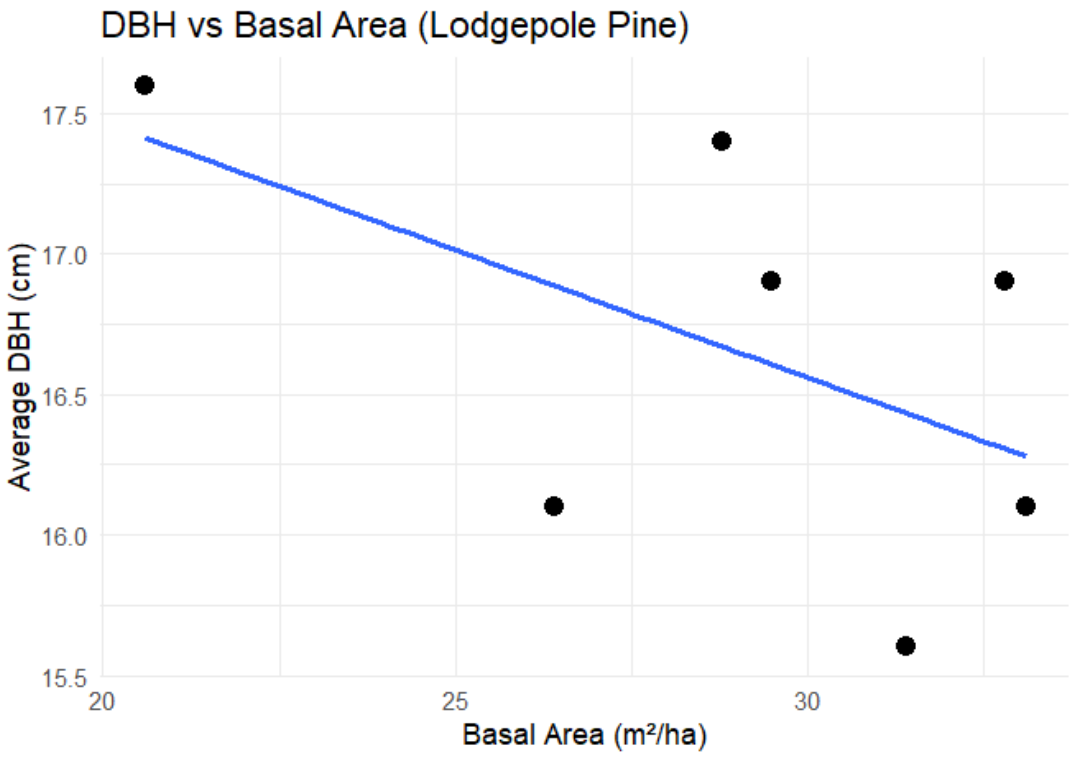

Figure 4 Relationship between average DBH and basal area for lodgepole pine.

DBH vs Ba/ha: $r \approx -0.53$, $p \approx 0.22$ (not significant)

Average DBH and basal area were not statistically significant ($r = -0.53$, $p = 0.22$), meaning that variability in average DBH was weakly correlated with basal area on a per hectare basis.

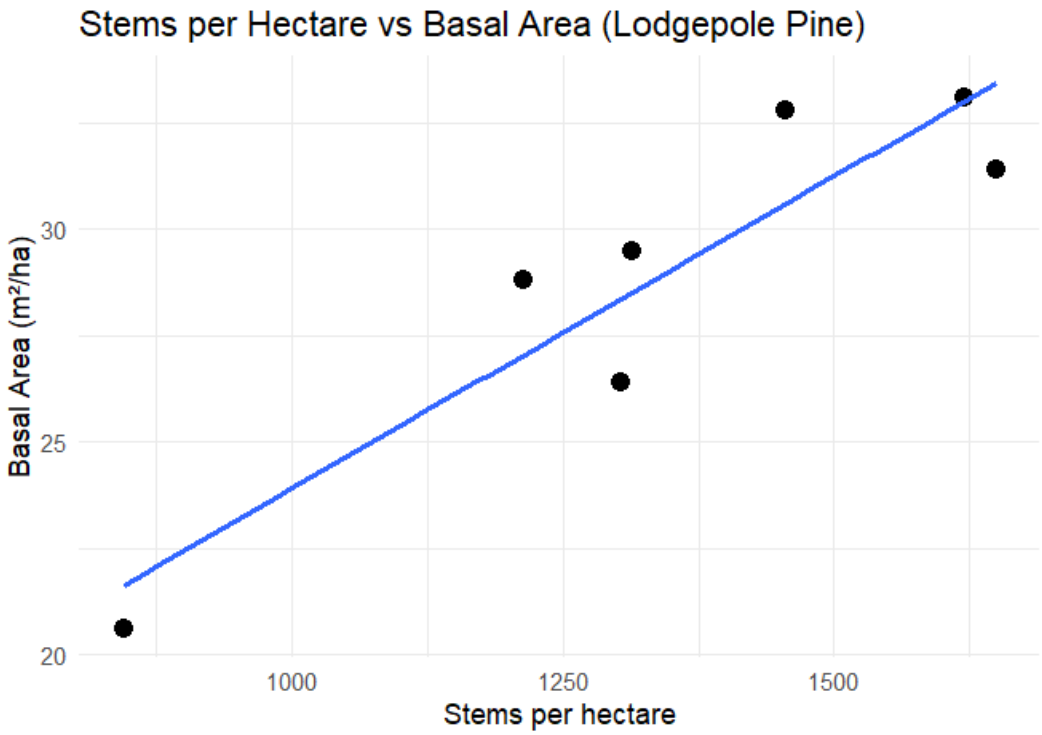

Figure 5 Relationship between stems per hectare and basal area for lodgepole pine.

stems/ha vs Ba/ha: r ≈ 0.92, p ≈ 0.0036

Stems per hectare and basal area were strongly and significantly positively correlated (r = 0.92, p = 0.0036). This shows that differences in basal area among blocks are primarily driven by stem density rather than differences in tree size. Together, these patterns support the evaluation of thinning as a block-specific management tool.

TASS Model Results:

Changes in Stems Per Hectare

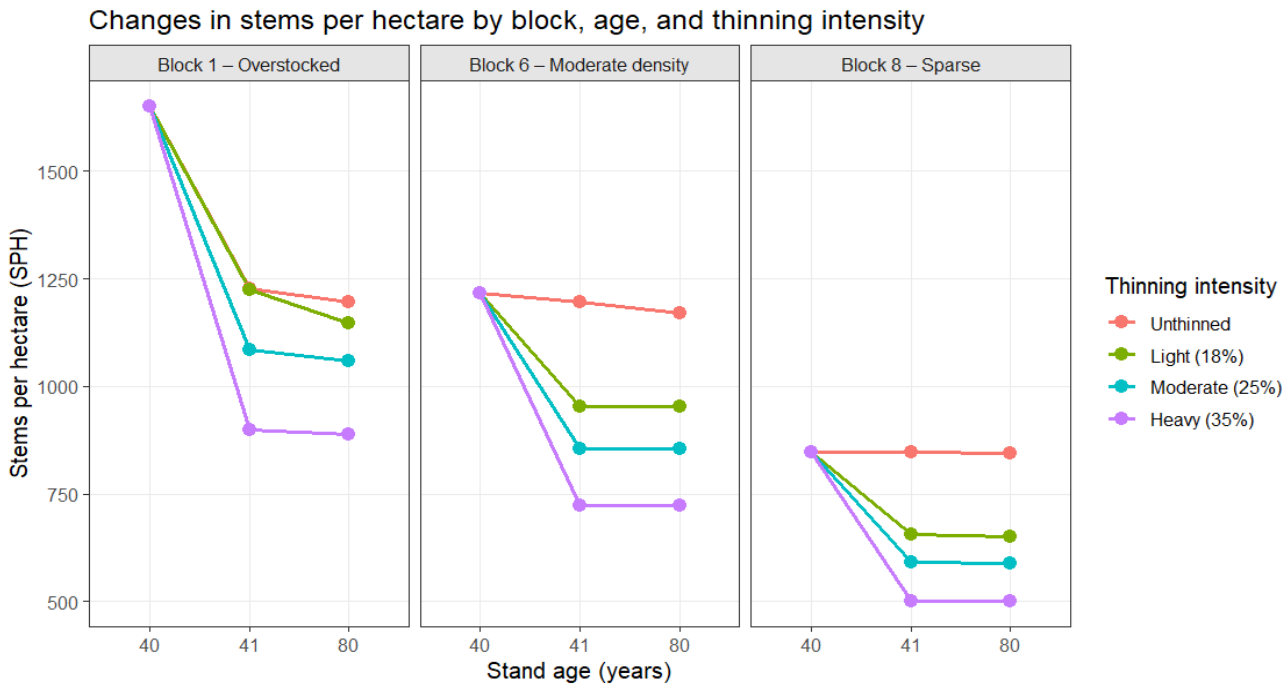

Figure 6 Changes in stems per hectare by block, stand age, and thinning intensity.

Block 1 exhibited high stand density at age 40 containing 1649 stems/ha. When this structure was used to initialize TASS, the model applied a self-thinning adjustment in the first simulation year, reducing density to 29.8 BA/ha. This reflects TASS's internal mortality algorithms for lodgepole pine under high density and mid-rotation size. The model determined that the stand composition was unsustainable and applied a natural thinning all in one year. Realistically this would gradually occur, however this outlines the unstable structure of LP stands such high density. All scenarios displayed an initial large dip in stems per hectare followed by a gradual decline. This die back occurred for all the scenarios around age 60 followed by a second smaller dip around age 74.

In Block 6 stem density declined only in response to thinning, as little natural mortality occurred in this block. All scenarios began at 1216 stems/ha at age 40. By age 41, densities dropped to 952 stems/ha in Scenario A, 856 stems/ha in Scenario B, and 724 stems/ha in

Scenario C, while the un-thinned stand remained unchanged. These post thinning densities remained stable throughout the projection. By age 80, stems per hectare were 1170 in the un-thinned stand, 952 in Scenario A, 856 in Scenario B, and 724 in Scenario C.

Block 8 showed that initial density was 848 stems/ha at age 40 across all scenarios. By age 41, the un-thinned stand remained at 848 stems/ha, while thinning reduced stems to 656 stems/ha in Scenario A, 592 stems/ha in Scenario B, and 500 stems/ha in Scenario C. Stem density remained constant following thinning, with final densities at age 80 of 844 stems/ha for the un-thinned stand, 652 stems/ha for Scenario A, 588 stems/ha for Scenario B, and 500 stems/ha for Scenario C.

Changes in DBH

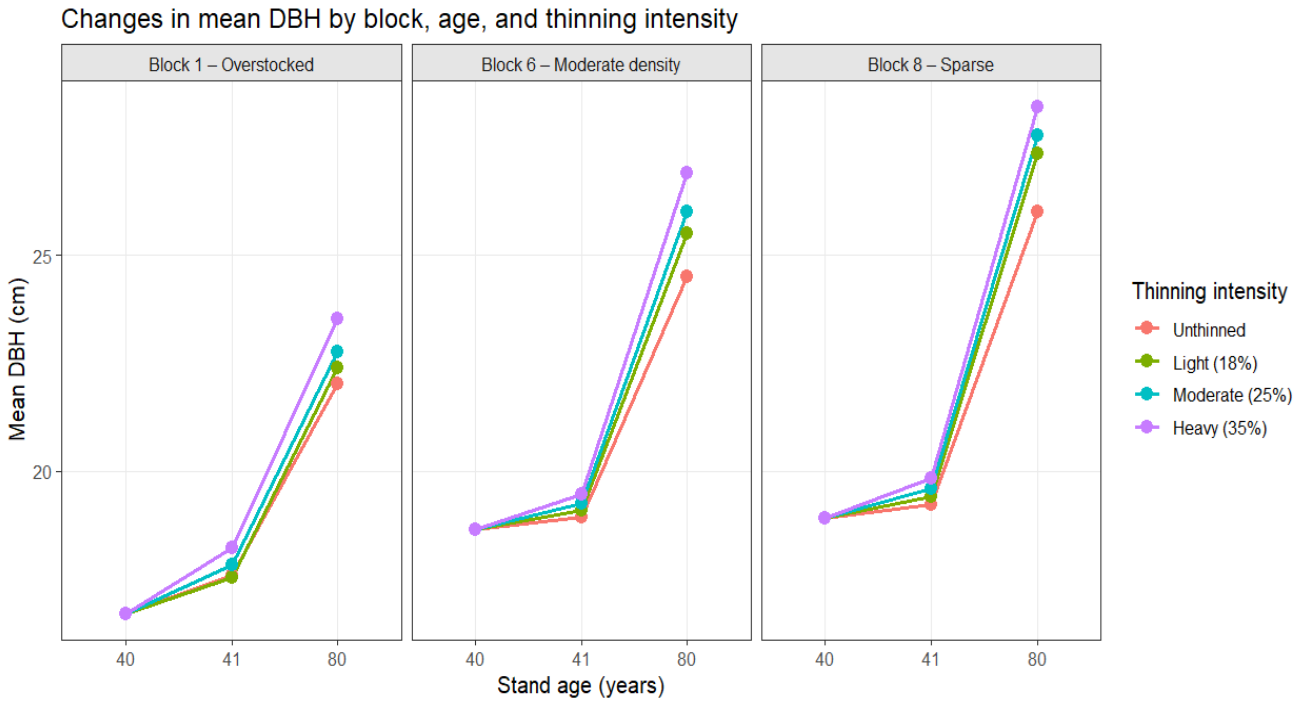

Figure 7 Changes in mean DBH by block, stand age, and thinning intensity.

Across all scenarios, mean DBH increased immediately following thinning (age 40-41). In Block 1 scenario C showed the largest first-year increase (+1.53 cm), followed by Scenario B (+1.15 cm), the un-thinned stand (+0.90 cm), and Scenario A (+0.86 cm). By age 80, DBH remained stratified according to thinning intensity, with Scenario C reaching the highest

mean DBH (23.53 cm), followed by Scenario B (22.76 cm), Scenario A (22.40 cm), and the un-thinned stand (22.03 cm).

Block 6 showed that mean DBH increased consistently across all scenarios, with the magnitude of early diameter response reflecting thinning intensity. All stands began at 18.65 cm at age 40. By age 41, DBH increased to 18.94 cm in the un-thinned scenario, 19.08 cm in Scenario A, 19.24 cm in Scenario B, and 19.46 cm in Scenario C. By age 80, DBH reached 24.50 cm in the un-thinned stand, 25.52 cm in Scenario A, 26.01 cm in Scenario B, and 26.91 cm in Scenario C. The strongest DBH response was associated with the heaviest thinning intensity.

In block 8 we see mean DBH increases across all scenarios immediately following thinning. Between ages 40 and 41, DBH rose from 18.9 cm to 19.22 cm in the un-thinned stand, 19.42 cm in Scenario A, 19.59 cm in Scenario B, and 19.84 cm in Scenario C. By age 80, DBH reached 26.0 cm in the un-thinned stand, 27.37 cm in Scenario A, 27.79 cm in Scenario B, and 28.45 cm in Scenario C, with higher thinning intensities associated with larger final diameters.

Changes in stems/ha due to thinning and mortality

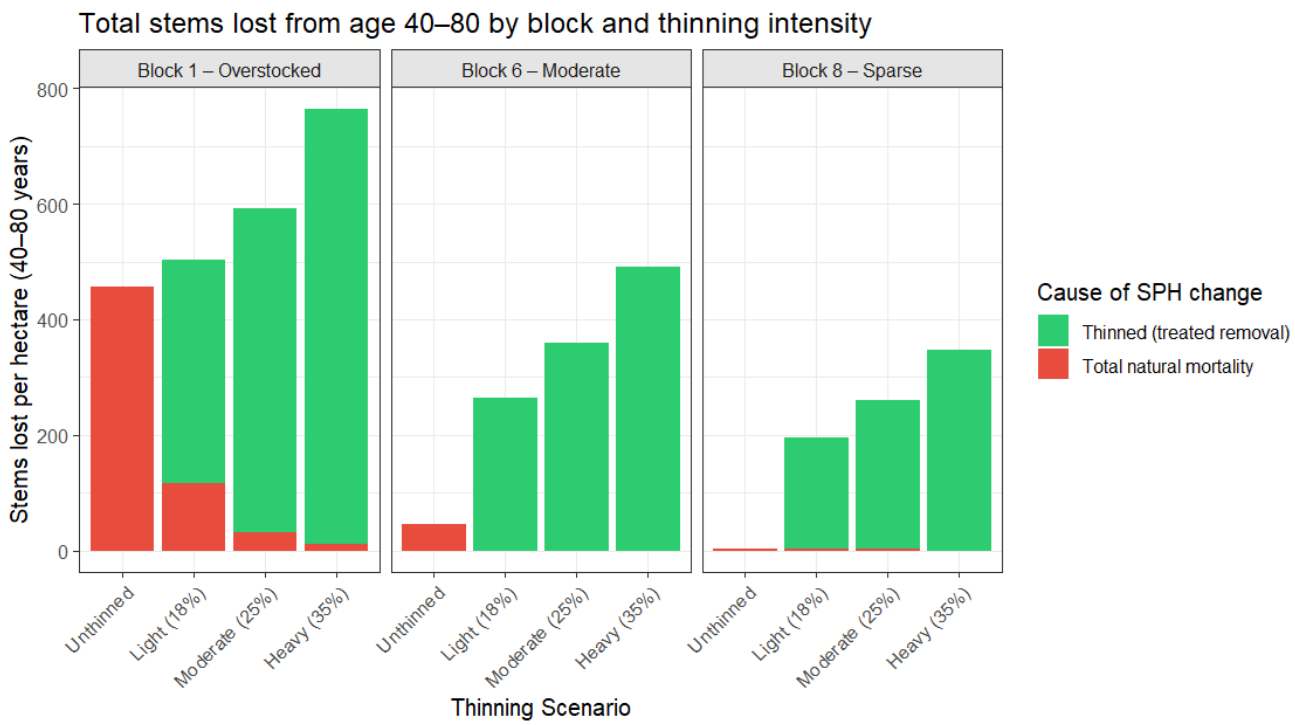

Figure 8 Total stems lost from ages 40–80 by block and thinning intensity.

In Block 1 the un-thinned scenario, lost 424 stems/ha (~25.7% of the initial 1652 stems/ha) and 6.3 BA/ha (~18%) due to competition-induced mortality early in the projection. In contrast, under the light thinning treatment (Scenario A, 18% BA removal), only 40 stems/ha or .79 Ba/ha (~2.1%) were lost to mortality over the same interval. Most of the density reduction in Scenario A was therefore achieved through deliberate thinning rather than natural self-thinning. Whereas Scenario B had only 8 stems/ha or .16 BA/ha (~0.4% of stems BA/ha) of loss due to mortality. While Scenario C had no initial loss due to mortality. This is likely due to the high volume thinned in scenario C (~35% of BA/ha) which reduced competition induced mortality.

Overall, we can see that there is significant loss within the un-thinned scenario. This is due to the high volume of stems/ha. The stand cannot maintain this high-density level and thus high levels of die off occurs. In contrast we can see that with higher levels of intentional thinning in scenarios A, B and C, there reduction mortality. The more intense the thinning, the less

natural thinning and die back occurs. Instead of losing this stand volume to natural thinning, commercial thinning would capture this volume.

Block 6 displays minimal mortality with only 20 stems/ha loss within the un-thinned scenario. Majority of this occurs after age 60 as the stand begins to self thin. Scenario A, B and C maintained no mortality throughout the planning period. Scenario A thinned 264 stems/ha, scenario B thinned 360 stems/ha while scenario C thinned 348 stems/ha.

Block 8 shows little natural mortality occurring in the between ages 40 and 41 or in subsequent years. The majority of reductions in stem density resulted solely from thinning treatments. Scenario A thinned 192 stems/ha, Scenario B thinned 256 stems/ha, and Scenario C thinned 348 stems/ha, corresponding directly to the increasing thinning intensities. Stem density remained constant after thinning for the remainder of the projection period.

Total Rotation Volume

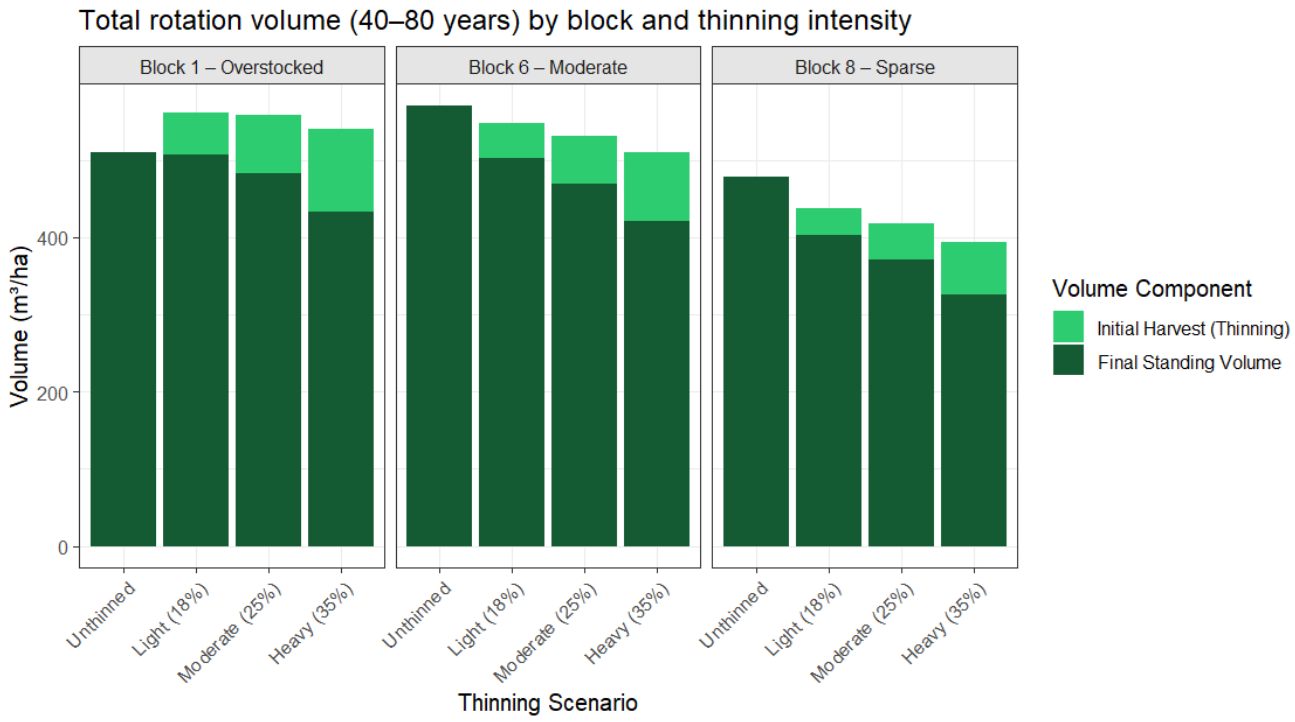

Figure 9 Total rotation volume (ages 40–80) by block and thinning intensity.

In block 1 volume declined sharply across all scenarios between ages 40 and 41. Scenario C exhibited the largest initial reduction (–107.1 m^3/ha), followed by Scenario B (–75.4 m^3/ha), Scenario A (–53.9 m^3/ha), and the un-thinned stand (–49.8 m^3/ha). Following this initial decline, volume increased steadily in all treatments through to age 80. Final volumes were highest in the un-thinned stand (509.9 m^3/ha), followed by Scenario A (507.6 m^3/ha), Scenario B (483.6 m^3/ha), and Scenario C (432.5 m^3/ha). The initial harvest volume through thinning seen in each scenario was 53. 9 m^3/ha in scenario A, 75.4 m^3/ha in scenario B and 107.1 m^3/ha in scenario C. When including this initial harvested volume in the final analysis we see an increase in volume under each thinning scenario (Light: 10.1%, Moderate: 9.6%, Heavy: 5.8%).

In block 6 total volume increased throughout the projection period in all scenarios despite the initial reductions associated with thinning. At age 40, volume was 268.9 m^3/ha across all scenarios. By age 80, total standing volume reached 570.2 m^3/ha in the un-thinned stand, 503.0 m^3/ha in Scenario A, 468.6 m^3/ha in Scenario B, and 420.7 m^3/ha in Scenario C. While thinning reduced standing volume, all scenarios demonstrated strong long-term growth and recovery. The initial harvest volume through thinning seen in each scenario was 44.6 m^3/ha in scenario A, 62.4 m^3/ha in scenario B and 88.7 m^3/ha in scenario C. When including this initial harvested volume in the final analysis there is still a decrease in volume under each thinning scenario (Light: -4%, Moderate: -7.9%, Heavy: 11%).

Total stand volume increased across all scenarios over the projection period, from an initial value of 203.9 m^3/ha at age 40to a total standing volume reached 477.6 m^3/ha in the un-thinned stand, 402.4 m^3/ha in Scenario A, 370.8 m^3/ha in Scenario B, and 326.0 m^3/ha in Scenario C by age 80. The initial harvest volume through thinning seen in each scenario was 34.5 m^3/ha in scenario A, 47.4 m^3/ha in scenario B and 67.2 m^3/ha in scenario C. When including this initial harvested volume in the final analysis a decrease in volume under each thinning scenario is maintained (Light: -8.6%, Moderate: -12.5%, Heavy: -17.7%).

Basal Area

Table 3 Basal area (m²/ha) by block, stand age, and thinning scenario.

Block	Age (yrs)	Un-thinned	Scenario A	Scenario B	Scenario C
1	40	36.1	36.1	36.1	36.1
	41	29.8	29.6	27.1	23.4
	80	45.6	45.2	43.2	38.8
6	40	33.2	33.2	33.2	33.2
	41	33.7	27.2	24.9	21.5
	80	55.1	48.7	45.5	41.2
8	40	23.8	23.8	23.8	23.8
	41	24.6	19.4	17.8	15.5
	80	46.33	38.4	35.7	31.8

In Block 1 basal area per hectare declined sharply across all scenarios following thinning or natural mortality between ages 40 and 41. The un-thinned stand experienced an 18% reduction in basal area due to self-thinning (36.1 to 29.8 m^2/ha). Scenarios A, B, and C showed immediate post treatment reductions consistent with their thinning intensities (18%, 25%, and 35%). By age 80, basal area recovered in all scenarios but remained varied based on thinning intensity. The un-thinned stand and Scenario A exhibited the highest final BA (45.6 and 45.2 m^2/ha), followed by Scenario B (43.2 m^2/ha) and Scenario C (38.8 m^2/ha). Overall, the basal area gained over the 40-year growth period was highest in Scenario B (+16.1 m^2/ha), with similar increases in the un-thinned stand (+15.8), Scenario A (+15.6), and Scenario C (+15.4).

In Block 6 basal area increased over time in all scenarios, although the immediate post-treatment values differed substantially due to thinning intensity. At age 40, all scenarios began at 33.2 m^2/ha. By age 41, basal area rose slightly to 33.7 m^2/ha in the un-thinned stand, while Scenario A decreased to 27.2 m^2/ha, Scenario B to 24.9 m^2/ha, and Scenario C to 21.5 m^2/ha. By age 80, basal area reached 55.1 m^2/ha in the un-thinned stand, 48.7 m^2/ha in Scenario A, 45.5 m^2/ha in Scenario B, and 41.2 m^2/ha in Scenario C. Although all thinned stands showed strong recovery, heavier thinning resulted in lower basal area at rotation age.

Basal area increased from 23.8 m^2/ha at age 40 to 24.6 m^2/ha in the un-thinned stand by age 41, while the thinning treatments produced immediate reductions proportional to their

intensities. Scenario A decreased BA to 19.4 m^2/ha, Scenario B to 17.8 m^2/ha, and Scenario C to 15.5 m^2/ha in the year following treatment. By age 80, basal area increased in all scenarios, reaching 46.3 m^2/ha in the un-thinned stand, 38.4 m^2/ha in Scenario A, 35.7 m^2/ha in Scenario B, and 31.8 m^2/ha in Scenario C.

Discussion

Variation between blocks and species

Variation in species between blocks

Species-level variability analysis showed clear differences in how individual species contribute to stand structure across the seven blocks. Lodgepole pine (PL) was the most consistent and dominant species across all seven blocks. This reflects the monoculture nature of these managed stands. Basal area (CV = 15.10%) and stems per hectare (CV = 20.41%) showed low variability. While average DBH was the most consistent between the blocks (CV = 9.76%). This shows that in both structure and density pine is the most stable species. These tests confirm that Lodgepole pine is the primary driver of stand structure and dynamics.

In contrast, balsam fir (B) and spruce (S) showed substantially higher variation across all metrics. Balsam fir exhibited high variability in basal area (CV = 74.6%) and stems per hectare (CV = 76.8%), as well as large fluctuations in merchantable volume (CV = 86.4%). Spruce also showed high variability across the blocks, with CV values of 70.3% for basal area, 69.8% for volume, and 57.1% for stems per hectare. These high CV values indicate that both spruce and balsam fir occur inconsistently across all blocks. The presence of these species likely suggests influences of site-specific conditions, small scale disturbances, or localized competition. Overall, these high CV values show that both these species do not have meaningful contribution to the overall stand structure and dynamics.

Deciduous species were the most variable group overall. Their basal area CV was extremely high at 90.4%. While stems per hectare showed similarly large variation at 118.8%. These

patterns reflect the opportunistic, patchy nature of hardwood regeneration. Confirming that deciduous species do not significantly contribute to the structural make up of these mid-rotation conifer stands.

Minor species such as Cottonwood (AC), Aspen (AT), and Douglas fir (F) were extremely inconsistent between the blocks. Cottonwood and Douglas fir were only present in one block each, meaning CV calculations could not be performed. Aspen occurred in two blocks, although only contributing to ~3% of the total species distribution in each block. These species sparse and inconsistent occurrence suggests they play no significant role in current stand structure or future yield projections.

Overall, the stability of lodgepole pine contrasted with the high variability of all other species confirms that pine is the only species contributing consistently and predictably to stand structure. This strongly supports the decision to model each block individually in TASS while focusing growth projections on lodgepole pine. All other species are treated as minor, highly variable background components with no influence on long-term stand development.

Species diversity between blocks

Shannon diversity values ranged from H' = 0.22 to 0.80 across all blocks, indicating very low species diversity consistent with early to mid-rotation lodgepole pine stands. Species richness ranged from 2 to 5 species per block consistent with minimal species variation between blocks. Pielou evenness values (J' = 0.20–0.58) showed that species contribution was uneven. In all blocks, lodgepole pine accounted for 74–95% of total stand composition. The uneven distribution is due to the high variability of other species across the blocks. This gives further support to Lodgepole pine being the dominant species between the blocks. Collectively, these metrics confirm that lodgepole pine overwhelmingly dominates stand structure and that minor species do not meaningfully influence stand dynamics. This supports the decision to model the TASS simulations under a lodgepole pine monoculture. Minor species, including balsam fir, spruce, and all deciduous components were excluded from TASS growth projections. Analysis on species variation showed extremely high

coefficients of variation (CV ≈ 57%–118%) and inconsistent occurrence across blocks. This high variability indicates that these species contribute irregularly and do not influence stand structure at mid rotation. In contrast, lodgepole pine exhibited low variability across all structural metrics (BA CV = 15%, DBH CV = 9.8%, stems/ha CV = 20%), confirming that pine is the only species contributing consistently and predictably to stand development. As a result, all TASS simulations focus exclusively on lodgepole pine, which is the primary driver of current and future stand dynamics.

Difference between blocks

When analysing the differences between the seven sampled blocks, the one-way ANOVA results showed significant compositional differences. Stems per hectare displayed significant differences across the blocks ($F = 23.67$, $p = 0.0046$). This could indicate a variability in initial stocking densities, site index or disturbance patterns. Average DBH also differed significantly across the blocks ($F = 10.02$, $p = 0.025$). This demonstrates that tree size distributions vary among blocks as tree size is largely influenced by stand density. Competition highly influences the growth rates of trees. Thus, the variation in stem density across blocks will produce variability in size distribution (Bettinger et al., 2017).
Net merchantable volume did not display a significant trend ($F = 4.20$, $p = 0.0958$), but $p<0.10$ may indicate a marginal trend in this category. This suggested that there is no pronounced difference between blocks, but productivity may show more significant differences as the stand ages. Basal area ($p = 0.266$) and total height ($p = 0.146$) did not differ significantly among blocks. This indicates that despite variability in density and diameter, overall growing stock and height development remain relatively consistent across stands. This makes sense as there is usually little variation in tree heights within even-aged stands. Since tree ages are effectively the same the stand structure will remain simple and height will not vary (Bettinger et al., 2017).
Collectively, these results demonstrate that substantial structural variability between blocks does exist. Variability in density and DBH justify the treatment of each block as distinct units

in TASS growth modeling. This significant difference in stems per hectare and average DBH show the importance of evaluating thinning needs and intensities on a block-by-block basis.

Correlation between metrics of LP

The Pearsons correlation tests were significant for both Stems per hectare Vs average DBH ($r = -0.82$, $p = 0.023$) and stems per hectare vs Basal area per hectare ($r = 0.92$, $p = 0.0036$). There was a strongly negative correlation between stems per hectare and average DBH. Meaning that the smaller the trees are the higher the number of stems per hectare is. Again, this density size dynamic is consistent with prior literature stating that average stand DBH is strongly linked to competition between trees (Bettinger et al., 2017). This made it easy to assess three levels of stand density. Highly stocked stands such as block 1 contained the highest number of stems per hectare while also containing the smallest average DBH. Conversely low stocked stands such as block 8 showed the lowest density of stems per hectare but had the largest trees present. This distinction allowed for the analysis of the effects of thinning treatments at multiple density ranges.

TASS Model

Overstocked stand – Block 1

Block 1 displayed significant overstocking qualities, containing an initial 1652 stems per hectare. In the first year following treatment we can see an expected drop in stems per hectare, basal area per hectare and total volume each thinning scenario (Shown in appendix A, B, C). This makes sense as the thinning had removed stems from the stand which results in the expected drop in volume. Unexpectedly the un-thinned scenario experienced a significant drop in volume as well. This behaviour is consistent with density-dependent self-thinning. At the combination of stand density (~1,650 stems ha) and tree size (DBH≈ 16–17 cm) at age 40. The stand is likely above the threshold that can be supported given size of trees present. In Stand Density Management Diagrams (SDMD) this threshold is known as the zone of

imminent mortality (ZIM). The point in which size and density force a competition induced natural thinning of the stand (BC Ministry of Forests, 1999). TASS operates on crown competition relationships which detected this initial density above the ZIM and deemed the stand infeasible. As a result, the model expresses self-thinning as a sharp mortality event early in the simulation, rather than as a gradual decline over multiple years. Once density has been reduced to ~1,220 stems/ha, subsequent natural mortality is reduced, suggesting that the stand has reached an equilibrium near full site occupancy.

In contrast, we see minimal mortality under each thinning scenario. Scenario A contained 40 stems of mortality, while Scenario B showed 8 and Scenario C had none. We can assume that mortality is linked to stem density. When a block is thinned, the potential mortality due to competition is reduced, and therefore mortality decreases. This is most clearly demonstrated in Scenario C, where the heaviest thinning resulted in no mortality. While the lightest thinning scenario exhibited the most mortality among the treatments. From this, we can conclude that thinning reduces mortality in overcrowded stands by alleviating competitive pressure. This stocking density is further confirmed when looking at SDMD for lodgepole pine. Under the size and density distribution the lower limit of the ZIM is ~1200-1300 stems/ha (BC Ministry of Forests, 1999). Meaning that the un-thinned block self thins to this threshold resulting in minimal future mortality. While the other scenarios reach bellow this threshold through removing stems from the stand.

There is also a strong DBH response to thinning in this overstocked stand. We see an immediate increase in DBH from age 40 to 41. The removal of smaller stems through thinning and natural mortality causes an increase in the average DBH. By age 80, thinning intensity produced a clear difference in stem size and stand structure. The un-thinned stand showed the smallest overall DBH increase at 4.45 cm, while the heaviest thinning scenario resulted in the largest increase at 5.32 cm. This pattern mirrors the mortality results, the more intensive the thinning treatment, the greater the DBH growth response. These findings are supported by previous literature. Bettinger and colleagues note that growth responses in even-aged stands are primarily dictated by competition among individual trees (BC Ministry of Forests, 1999). We observe the same pattern in this overstocked block. The more competition is reduced

through thinning, the stronger the resulting growth response. This is further supported by the previous Pearson's correlation tests, which showed that stem density was significantly negatively correlated with DBH.

Basal area showed a sharp decline in the un-thinned stand due to the intense self-thinning event, while the thinned scenarios experienced proportional reductions based on treatment intensity. Although all stands recovered basal area steadily afterward, the heavily thinned stand maintained the lowest BA throughout the projection period, reflecting its reduced initial growing stock. By age 80, BA clearly diverged among treatments, with lighter thinning maintaining BA trajectories much closer to the un-thinned stand.

As expected, total volume shows a reduction with higher amounts of thinning. This is logical, as removing more stems decreases total standing volume. The un-thinned, lightly thinned, and moderately thinned scenarios all show similar total volume gains post-treatment, at approximately ~233 m^3/ha. The heavy thinning scenario shows the smallest increase in volume at 212.8 m^3/ha (See appendix C). This demonstrates that even when trees grow larger, this does not always translate into a corresponding increase in total volume. However, these reductions in standing volume must be interpreted alongside thinning removals. The 18–35% thinning treatments recovered a portion of the volume that the un-thinned stand lost through self-thinning mortality, meaning total produced volume (thinning removals + final standing volume) would be more comparable across scenarios. When looking at final standing volume in conjunction with thinned volume we see an increase in each thinning scenario (Light: 10.1%, Moderate: 9.6%, Heavy: 5.8%). Given this, we can assume that although the un-thinned stand and Scenario A achieved similar final volumes, the volume recovered through the initial thinning harvest would make Scenario A the more favorable option of the two.

Thinning influenced overall stand structure by reducing density and increasing growing space. This allows for improved light availability and resource access for residual trees. These structural changes promoted larger crowns and enhanced diameter growth in more heavily thinned treatments. In contrast, the un-thinned stand maintained a more competitive environment, limiting individual tree growth despite retaining higher overall density and basal area.

Overall, thinning in this overstocked stand reduced early mortality, increased mean tree size, and produced higher total harvestable volume. Light and medium thinning provided structural benefits with minimal reductions in final standing volume. While heavy thinning generated the strongest diameter response at the cost of reduced number of stems and lower overall stand volume.

Moderate – Block 6

Block 6, a moderately stocked stand, shows notable differences in stems per hectare throughout the 40-year projection period. Each thinning scenario maintains its post treatment density, indicating that the treatments reduced stem density to a sustainable level for the remainder of the rotation. The un-thinned stand shows an initial decrease of 20 stems per hectare, followed by an additional reduction of 26 stems over the rest of the planning period. After this early mortality, the un-thinned stand maintains a steady stem density until around age 63, where further losses occur. This suggests that between ages 41 and approximately 63, the stand is at an appropriate stocking level at around 1196 stems/ha. This is in line with SDMD data which suggests that stem density should be below ~1250 stems/ha at age 40 (BC Ministry of Forests, 1999). After age 63, competition increases again due to the maturing stand, leading to further but more gradual mortality (See Appendix A). This indicates that lodgepole pine stands older than 63 years cannot maintain densities above ~1196 stems/ha without experiencing density-driven mortality.

As in the other stands, there is a strong DBH response to thinning. Consistent with prior results, there is a clear relationship between stem density and average DBH. The thinning treatments produced noticeable increases in diameter growth, with total DBH gains of 5.85, 6.87, 7.36, and 8.26 cm across the un-thinned, light, moderate, and heavy thinning scenarios, respectively.

Volume dynamics reflected the expected trade-off between early stem reductions from thinning and long-term recovery. All thinning scenarios experienced an initial drop in volume, but each showed strong recovery through mid- and late-rotation growth. The un-thinned

scenario maintained full stocking throughout the projection period and demonstrated continuous increases in both basal area and volume. This confirms that the stand was not operating above the ZIM threshold. Importantly, the lower standing volumes observed in thinned scenarios again must be interpreted in the context of harvested volume removed during thinning operations. When analysing both initial thinned volume and total standing volume there is a noticeable drop in volume when thinning occurs (Light: -4%, Moderate: -7.9%, Heavy: 11%). This further supports the un-thinned stand operating below the ZIM as thinning operations do not capture additional volume otherwise lost through mortality as seen in Block 1.

Overall, thinning enhanced diameter growth and reduced late rotation mortality without reducing long-term productivity. However, because the stand was not under significant density pressure, the structural benefits of thinning were less pronounced than those observed in the overstocked Block 1. These results suggest that thinning can improve tree size and stand structure in moderately stocked stands. But its necessity and intensity should be guided by management objectives rather than the need to address density stress. The un-thinned block maintained stable stem density throughout most of the planning period while also achieving the highest total volume. From this we can infer that thinning is not immediately necessary in this block and that it is currently at an appropriate density level. Thinning may become beneficial later in the rotation as the stand enters the ZIM and experiences self-thinning around age 63. Again, future management directions will dictate the appropriate treatment given the desired outcomes.

Understocked stand – Block 8

Block 8 represents an understocked lodgepole pine stand where the initial density was below typical mid-rotation conditions (BC Ministry of Forests, 1999). With approximately 848 stems per hectare at age 40, the stand was not experiencing meaningful competition. This is inferred from the minimal mortality across all scenarios throughout the entire projection period. Block 8 showed no initial mortality associated with thinning treatments, which

contrasts sharply with the overstocked Block 1. This highlights that the block was operating well within the biological carrying capacity below the ZIM. Because density was not a limiting factor, mechanical removal of stems was the only driver of structural changes. Across the scenarios, only a small decline of 4 stems per hectare occurred in the un-thinned stand, Scenario A, and Scenario B, while Scenario C had no mortality at all. This small amount of mortality is likely due to normal competitive processes, though greatly reduced compared to the other blocks. The absence of mortality in the heavily thinned Scenario C suggests that this treatment reduced the stand density well below the ZIM for the entire growing period.

The thinning scenarios produced proportional reductions in stem density, but unlike the other stands this came with no beneficial mortality reduction or volume gain. All scenarios maintained stable stem density from age 41 onward, reflecting a stand that was never dense enough to undergo self-thinning at any point in the rotation. This stability suggests that even after thinning, the stand remained below the ZIM threshold at which lodgepole pine typically experiences density dependent mortality. As a result, the benefits of thinning in Block 8 were considerably less pronounced than in stands with higher initial stocking.

Similar to the other blocks, DBH responded positively to thinning, with the significance of the response reflecting thinning intensity. Diameter growth over the projection period was 8.47 cm, 8.89 cm, and 9.55 cm for Scenarios A through C. However, the un-thinned stand also displayed substantial DBH growth, increasing by 7.1 cm despite the lack of thinning. This further supports the conclusion that the stand is operating at or below the ZIM. Block 8 consistently produced the largest DBH values across all treatment categories; however, this occurred at the expense of total volume. This block contained the lowest final standing volumes of all stands, with values of 477.6, 402.4, 370.8, and 326.0 m^3/ha across the un-thinned, light, moderate, and heavy thinning scenarios. Even when including initial volume attained through thinning, each scenario shows a significant reduction when compared to un-thinned scenario (Light: -8.6%, Moderate: -12.5%, Heavy: -17.7%).

These volume dynamics reinforce the limited benefits of thinning in an understocked stand. The un-thinned stand consistently maintained the highest standing volume throughout the projection period. While thinned stands did recover volume, the rate of accumulation was

too slow to surpass the un-thinned scenario. This is due to the large number of stems being removed from the stand, resulting in significant volume loss which cannot be made up in size alone. Block 8 clearly reflects this outcome as thinning reduces the number of residual trees far below the carrying capacity of the stand.

Overall, the response of Block 8 demonstrates that thinning provides limited structural or productivity benefits in understocked lodgepole pine stands. Although thinning produces a slight increase in individual tree size, these gains are outweighed by reductions in total stem density and standing volume. Even when considering initial harvest volume, the un-thinned scenario is far more productive than subsequent scenarios. Because the stand was never competition limited, thinning did not meaningfully alter development or improve stand vigor. These results indicate that thinning an understocked mid-rotation stand is not advisable. If specific management objectives prioritize individual tree size rather than total yield, thinning could be recommended to meet these objectives. For Block 8, the un-thinned scenario is clearly the most efficient and productive option given the stand's already low stocking level.

Overall takeaways

Stand density determines natural mortality.

When comparing all three blocks, a clear pattern emerges, stand density strongly dictates natural mortality. The highest mortality occurred in the densely stocked stands Block 1 (424 stems lost) and Block 6 (approximately 20 stems lost) whereas the understocked Block 8 experienced minimal mortality throughout the projection period. This indicates that at age 40, stands with densities near or above ~1,600 stems/ha are above the ZIM, resulting in density-induced stem loss. In contrast, Block 6's low initial mortality suggests that a density of roughly 1,200 stems/ha is near the threshold at which lodgepole pine can maintain full stocking without experiencing significant competition related mortality.

This interpretation aligns with previous research on competition in lodgepole pine. Studies have shown that mortality is substantially reduced in stands with canopy gaps. In closed canopy conditions there is a reduction of available light, soil moisture, and nutrient access,

resulting in growth limitations (Harper, et al., 2009). Furthermore, according to the SDMD of lodgepole pine, stands at similar size and age classes to the sampled blocks maintain highest productivity and lowest mortality in stem densities of ~900-1200 stems/ha (BC Ministry of Forests, 1999). Together, these findings reinforce that stand density at mid-rotation is the primary driver of natural mortality, and that thinning, when applied to dense stands, serves to maintain stocking levels below the zone of imminent mortality.

Thinning intensity determines diameter growth.

When examining tree size relative to thinning intensity, we see the same relationship as identified in earlier Pearson's correlation analysis between DBH and stems per hectare; Stands with lower stem density consistently produce larger trees. This pattern holds across all three blocks. Thinning treatments, regardless of intensity, increased average DBH. In addition, each stand showed a clear and progressive trend in which reduced density led to larger diameter growth.

Waghorn et al. reported similar results, observing that DBH in 17-year-old lodgepole pine stands declined from ~36 cm to ~17 cm as stem density increased from ~200 to ~2,000 stems per hectare. The current study mirrors this relationship, providing further evidence that tree size in lodgepole pine is strongly and predictably influenced by stand density (Waghorn et al,. 2007).

Final volume depends on initial stocking

There are clear differences in total volume production among the three blocks. This reflects how stand density influences standing volume, mortality, and harvested yield. In the overstocked Block 1, the un-thinned scenario produced a total of 509.9 m^3/ha. Whereas thinning scenarios produced substantially higher totals: 561.5 m^3/ha in Scenario A, 559 m^3/ha in Scenario B, and 539.6 m^3/ha in Scenario C. This happens because of density-driven mortality in the un-thinned stand resulting in the loss of merchantable volume. In contrast, the thinning treatments removed stems before mortality occurred, converting what would

have been lost to self-thinning into merchantable harvested volume. As expected, thinning an overstocked stand improves total volume production. Therefore, thinning should be considered essential to avoid losing potential yield in similar blocks.

In the moderately stocked Block 6, total volume outcomes show a more balanced response. The un-thinned scenario produced the highest total volume at 570.2 m^3/ha. This is followed by 547.6 m^3/ha in Scenario A, 531 m^3/ha in Scenario B, and 509.4 m^3/ha in Scenario C. Due to Block 6 exhibiting very little mortality prior to age 63, thinning did not capture volume that would otherwise be lost to self thinning events. Instead, thinning simply redistributed growing stock among fewer trees, increasing individual stem size but reducing total stand level yield. In this case, a light thinning, or delaying thinning until natural mortality begins would be the best fit for similar blocks.

Block 8, the understocked stand, shows the opposite pattern. The un-thinned scenario produced 477.6 m^3/ha, while thinning scenarios A through C declined to 436.9**,** 418.2, and 393.2 m^3/ha. With little to no density induced mortality at any point, thinning only removed merchantable stems. This limits standing volume in the forest without generating a significant and compensating growth response. As a result, total volume declined with thinning intensity. This confirms that thinning an understocked mid rotation stand is counterproductive if the objective is to maximize total yield since reductions in stems cannot be offset by growth gains in trees.

Recommendations:

Overstocked - Block 1 recommendations:

When looking at Block 1, there is an understanding that high mortality occurs in the un-thinned scenario due to high density-induced competition. When thinning treatments occur, we see a significant DBH increase in relation to the number of stems thinned from the stand. With these thinning treatments comes an increase in volume too. When analysing total standing volume in conjunction with harvested volume through thinning treatments, the total volume available for capture is greater than seen in the un-thinned stand (Light: +10.1%,

Moderate: +9.6%, Heavy: +5.8%). Due to these findings, a thinning is recommended to attain the highest volume levels, reduce mortality, and increase average tree size. A light thinning would be most beneficial, as this scenario has the least reduction in stems/ha, resulting in the highest standing volume present at the harvestable age of 80. In addition, a light thinning reduces mortality by harvesting highly competitive trees, which limit overall stand productivity. Overall, Block 1 would benefit from a thinning of ~18% BA removed, as this has the largest improvement on overall stand productivity.

Moderate - Block 6 recommendations:

The results in block 6 indicate a strong DBH response to thinning treatments. This is inline with prior findings that lower stand density increases the overall size of trees within it. Furthermore, we see that there is minimal post treatment mortality under any scenario. Majority of the mortality seen is present in the un-thinned scenario from age 60-65. Suggesting that the zone of imminent mortality has been crossed and self thinning is occurring. At this age, the stand has reached its carrying capacity and thus a thinning prior to this would be necessary to capture this otherwise lost volume. Due to these factors no initial thinning is recommended however, a delayed thinning around age 60-65 would be required to maintain stand productivity and avoid self thinning. Overall, the un-thinned scenario still maintains the highest volume at the end of the planning period. A delayed thinning treatment would allow for the capturing of lost volume at ages >60.

Sparse - Block 8 Recommendations

Again, in block 8 there is a strong DBH response to thinning treatments however, this comes at the cost of large volume loss withing the block. Results show that thinning creates strong structural changes due to the removal of stems from the stand. Due to the stand being well below its operating capacity, thinning the block provides no further benefits other than increasing the overall size of trees withing the block. For this reason, no thinning is recommended in this block.

Overall, there are significant differences between the how blocks are managed based on initial stem density. Blocks containing high density experience an increase in mortality and reduction in size due to overcrowding and competition. Thinning can help mitigate these effects while capturing otherwise lost volume. By reducing stem density, a resulting increase in DBH and decrease in mortality is seen. However, total volume depends on initial stand density. In overstocked blocks, reducing density allows for the increase in total volume due to the capturing of lost volume as seen in un-thinned block 1. Conversely, in a sparse block a thinning reduces stems/ha in an already understocked block which inevitably reduces volume as the stand cannot recuperate from the loss of stems in growth alone.

Future Management decisions:

This study seeks to inform future management decisions around stand density and thinning treatments. Overall initial stocking density will guide management decisions. Through understanding the SDMD of lodgepole pine in conjunction with these results, managing stem density to ~900-1200 stems/ha at age 40 is ideal to reduce mortality and maximise volume. The use of pre-commercial thinning, earlier commercial thinning or management of initial planting stock will allow for the optimal management of stand density. Overall early management decisions dictate mid and late rotation decisions. Through early silvicultural management, blocks may maintain full stocking capacity, maximizing productivity near the ZIM while also limiting self thinning. Future lodgepole pine stands should be managed with stem density as a focus to maximise volume and reduce stem loss.

Limitations

There are several limitations to this study, mainly associated with the TASS model, thinning intensities, and historic differences between the blocks.

TASS Model

Dramatic mortality shown in Block 1

The dramatic mortality shown in the first year in Block 1 is not realistic. The loss in SPH would

be ongoing from previous years and would show a sharp but gradual decline due to overcrowding of the stand.

No disturbance modeling

The inclusion of disturbances was left out of this study due to the stochasticity and noise it would create when recording the findings. Including disturbances would create unknown variables, which would ultimately cloud the results and cause the study to lose focus on its overall goal.

Potential error in modeling

There is always potential for error in modeling, both within TASS and through human error. Many assumptions were made to limit the influence of external variables. Thus, the findings presented in this report must be viewed as a modeling outcome and not real-world proof of stand development.

Thinning Intensities

Thinning intensities were simplified

Thinning intensities were simplified to reduce the number of models that needed to be run. A range of thinning intensities was modeled to reduce the complexity of this study. Overall, a greater number of thinning scenarios would be needed to fully understand which scenarios provide the most benefit to overall stand structure and volume production.

Historic Differences

Changes in silviculture treatments

Differences in silviculture prescriptions could influence how these stands develop, further affecting the productivity and growth rates of these blocks. Site preparation, PCT, fertilization, and other silviculture treatments can influence stand growth rates and thus impact the overall differences observed when modeling.

Site index

For this study, site index was generalized in order to better understand the differences that

thinning has at different stocking standards. Site index data were not made available, but values were calculated and averaged between the blocks to achieve a site index of 20.

Other biological differences

Other biological differences, such as disturbances, species composition, pathogens, and human involvement, were also left out of the study to reduce complications and improve the quality of the results.

Academic–Operational Disconnect

This study operates off modeling software, which may not accurately depict real-world scenarios or practices. Thinning percentages, skid trails, species compositions, block layout, and many other factors may influence the effectiveness of thinnings when practically implemented. In addition to this, management direction, incentives, and objectives may alter the practicality of implementing these thinning regimes.

Conclusion

This study demonstrates that stand density is the primary factor influencing stand structure, growth rates, mortality, and productivity of mid-rotation lodgepole pine stands. Thinning responses were strongly dependent on initial stocking. Overall, thinning captured lost volume and reduced mortality in overstocked stands, showed greatest benefits when delayed to ~60 years in adequately stocked stands, and reduced productivity in understocked stands. Overall, optimal management of lodgepole pine stands requires maintaining mid-rotation stem densities below the zone of imminent mortality. To maximize productivity, thinning should be used on a block-by-block basis to control overstocking. This study seeks to contribute to the management and thinning practices of lodgepole pine in order to maximize productivity and stand sustainability.

Acknowledgements

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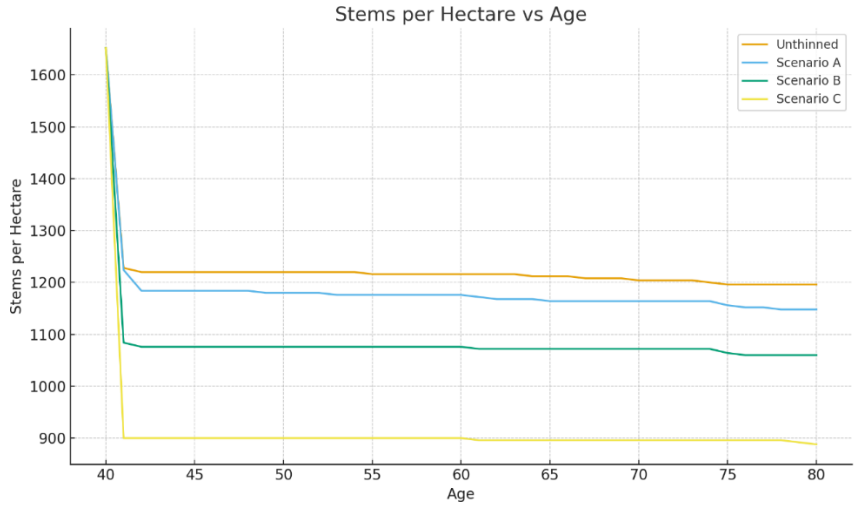
Appendix

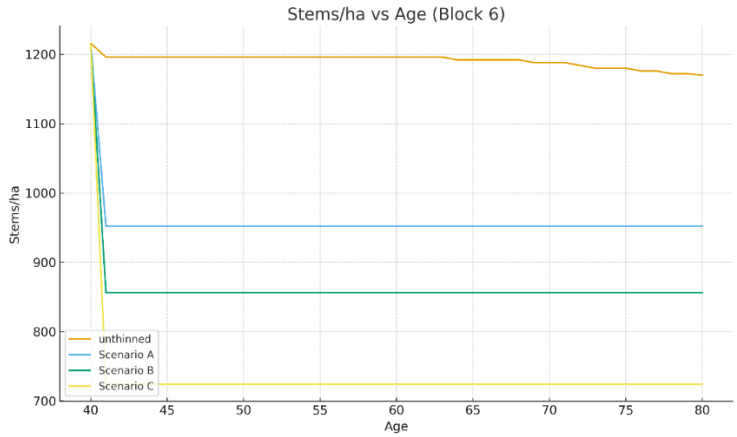
Appendix A: TASS Model stems/ha by Block

Block 1



Metric	Age	Un-thinned	Scenario A	Scenario B	Scenario C
stems/ha	40	1652	1652	1652	1652
stems/ha	41	1228	1224	1084	900
stems/ha	80	1196	1148	1060	888

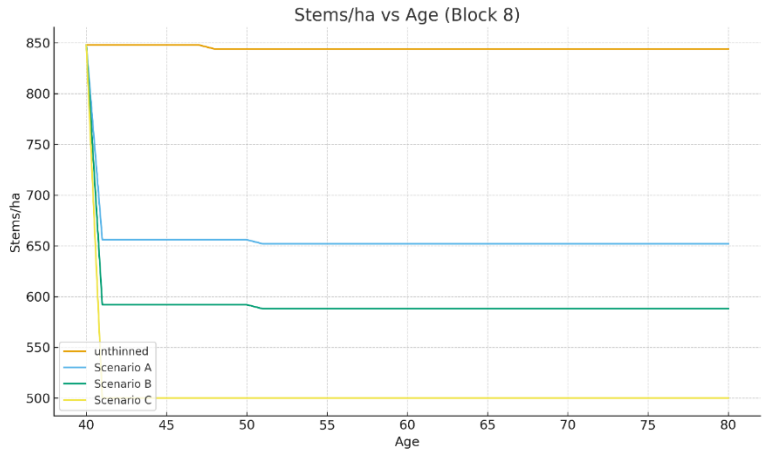
Block 6



Metric	Age	un-thinned	Scenario A	Scenario B	Scenario C

stems/ha	40	1216	1216	1216	1216
stems/ha	41	1196	952	856	724
stems/ha	80	1170	952	856	724

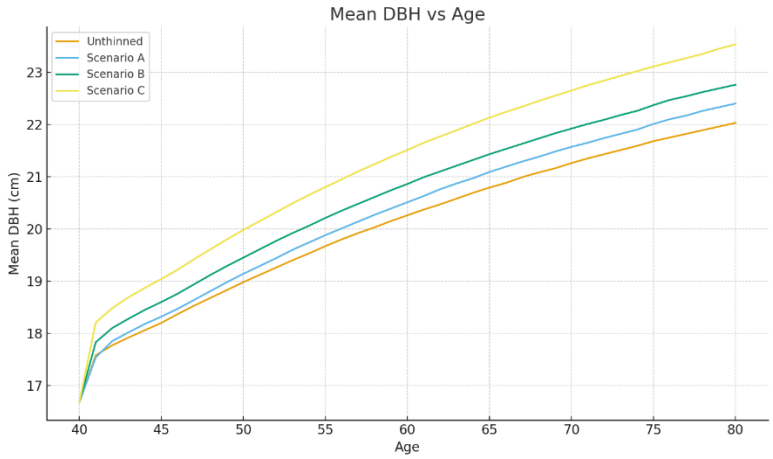
Block 8



Metric	Age	un-thinned	Scenario A	Scenario B	Scenario C
stems/ha	40	848	848	848	848
stems/ha	41	848	656	592	500
stems/ha	80	844	652	588	500

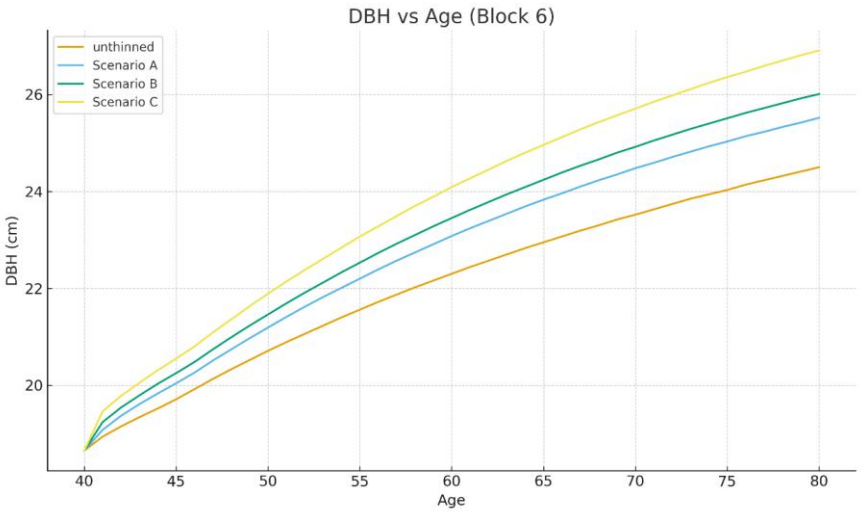
Appendix B: TASS Model DBH by Block

Block 1



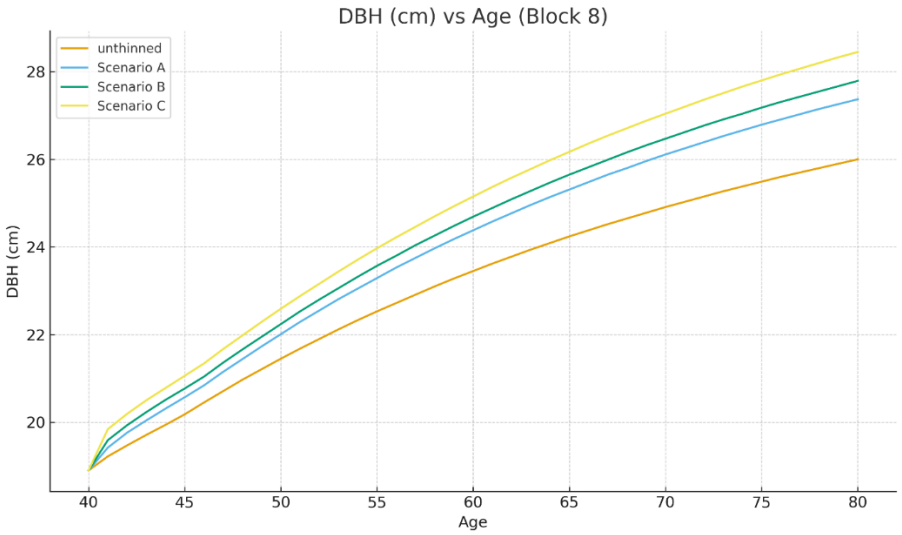
Metric	Age	Un-thinned	Scenario A (-18%)	Scenario B (-25%)	Scenario C (-35%)
DBH	40	16.68	16.68	16.68	16.68
DBH	41	17.58	17.54	17.83	18.21
DBH	80	22.03	22.4	22.76	23.53

Block 6



Metric	Age	unthinned	Scenario A	Scenario B	Scenario C
DBH	40	18.65	18.65	18.65	18.65
DBH	41	18.94	19.08	19.24	19.46
DBH	80	24.5	25.52	26.01	26.91

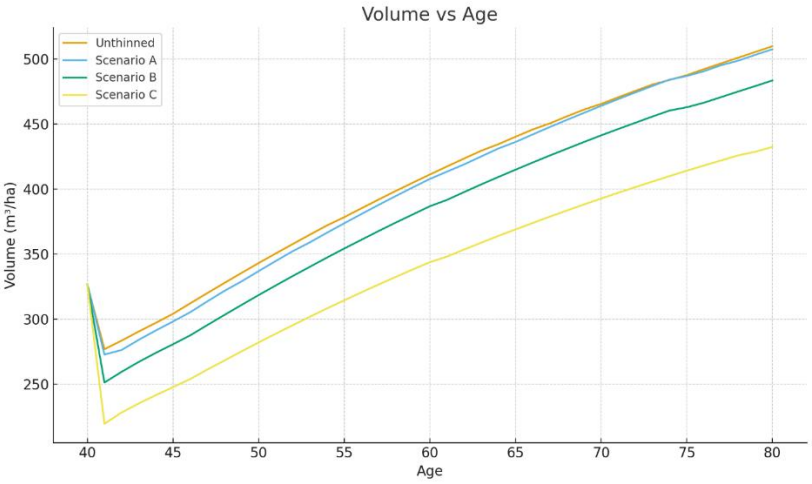
Block 8



Metric	Age	unthinned	Scenario A	Scenario B	Scenario C
DBH	40	18.9	18.9	18.9	18.9
DBH	41	19.22	19.42	19.59	19.84
DBH	80	26	27.37	27.79	28.45

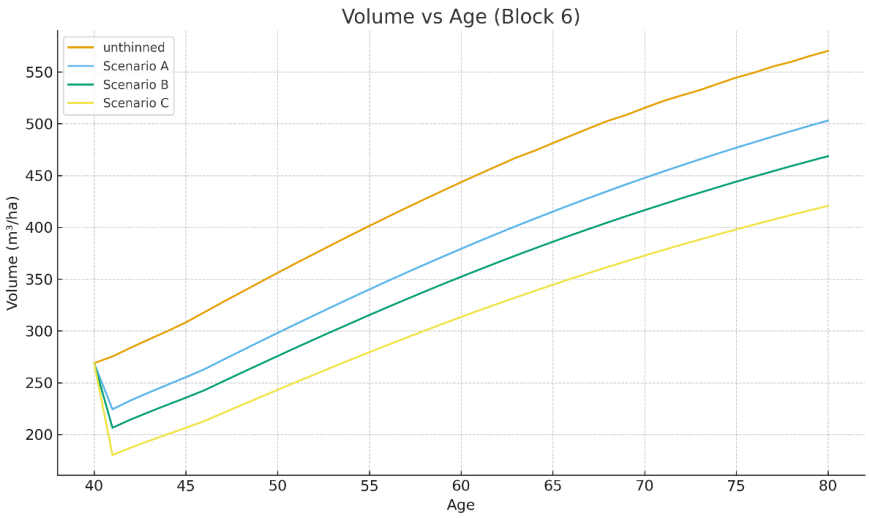
Appendix C: TASS Model Volume by Block

Block 1



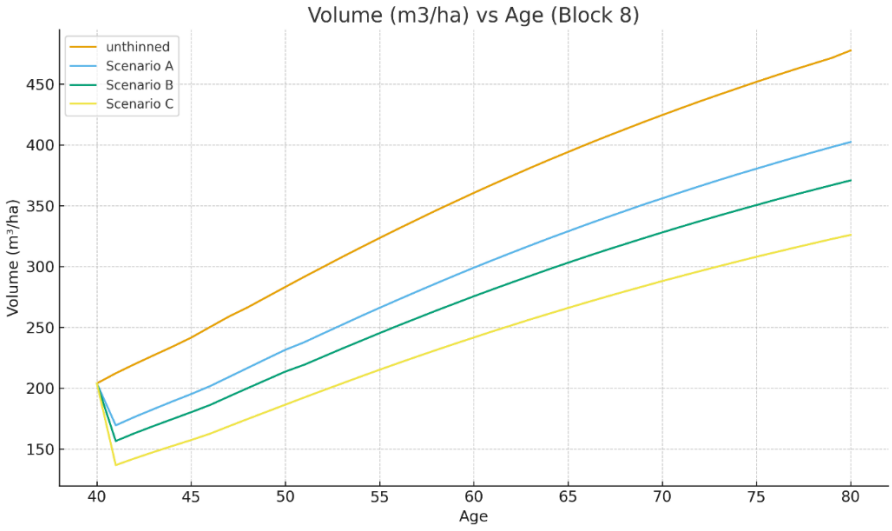
Metric	Age	Un-thinned	Scenario A	Scenario B	Scenario C
Vol	40	326.8	326.8	326.8	326.8
Vol	41	277	272.9	251.4	219.7
Vol	80	509.9	507.6	483.6	432.5

Block 6



Metric	Age	unthinned	Scenario A	Scenario B	Scenario C
Vol	40	268.9	268.9	268.9	268.9
Vol	41	275.3	224.3	206.5	180.2
Vol	80	570.1667	503	468.6	420.7

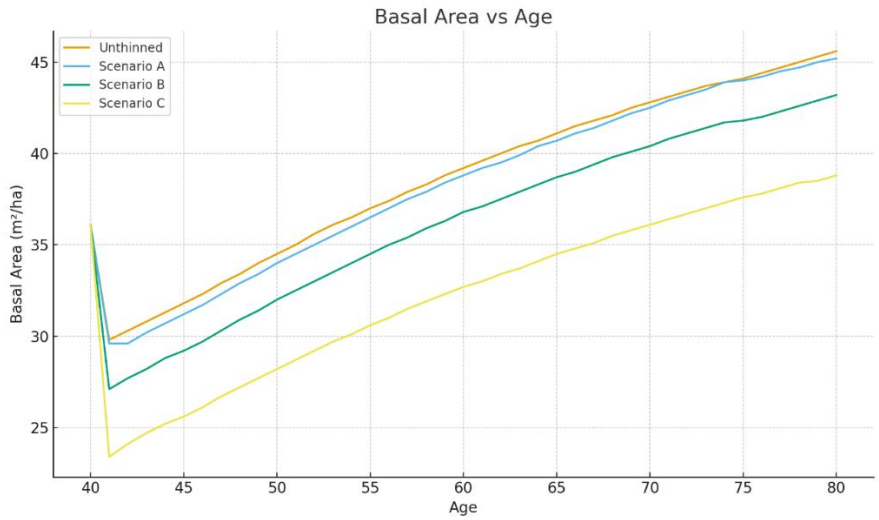
Block 8



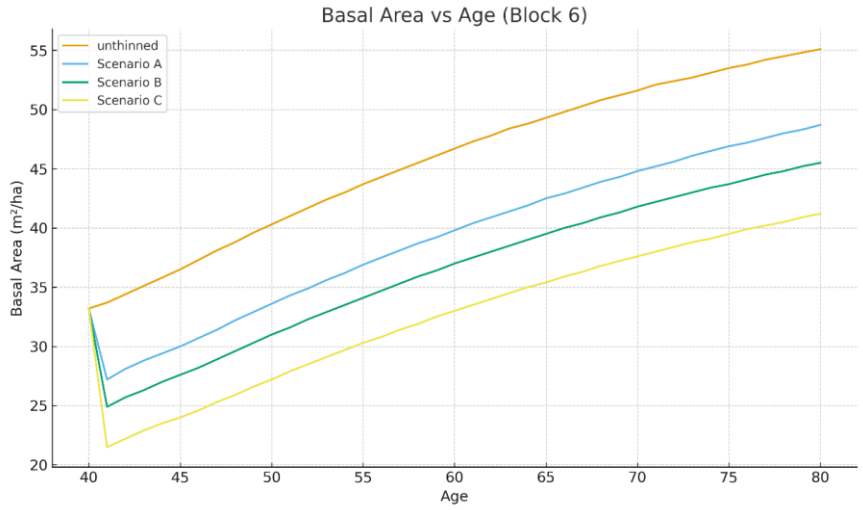
Metric	Age	unthinned	Scenario A	Scenario B	Scenario C
Vol	40	203.9	203.9	203.9	203.9
Vol	41	212.2	169.4	156.5	136.7
Vol	80	477.6473	402.4	370.8	326

Appendix D: TASS Model BA by block

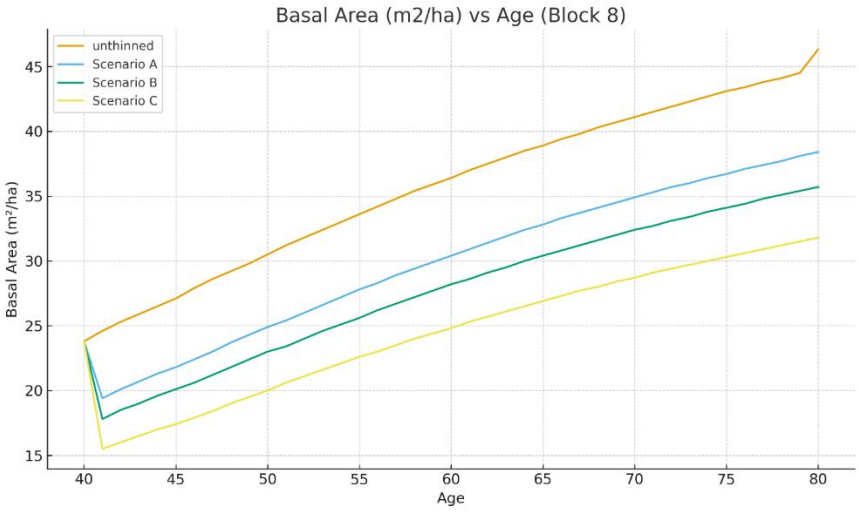
Block 1



Block 6



Block 8


Basal Area (m2/ha) vs Age (Block 8)
unthinned
Scenario A
Scenario B
Scenario C
Basal Area (m²/ha)
Age
15
20
25
30
35
40
45
40
45
50
55
60
65
70
75
80