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MSc Spatial and Ecological Modelling in European Forestry

Modelling Commercial Thinning (CT) regimes for timber production in interior British Columbia, Canada

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Abstract

The forestry sector plays an important role in British Columbia's economic, social and cultural aspects. Forests in the province account for 60% of the land cover and nearly 95% of this land is owned by the Crown. Recent natural and human-induced events, such as Mountain Pine Beetle infestations and wildfires, affected timber supply, opening space for different management regimes that can help mitigate this gap and also promote more resilient and productive forests. Using SORTIE-ND, this study aims to model thinning regimes in interior British Columbia by changing 5 management variables: skidding track distance; frequency (f); intensity (i); method and continuous cover forestry. We based our standards and thresholds on BC's Commercial Thinning Guidelines, and found that the skidding track as well as the model's randomness did not play an important role in the results. Thinning from above fulfilled every requirement of the guideline and produced, in every situation, a higher stand volume than unthinned regimes. Thinnings from below did not fulfill the requirements in higher intensities and higher frequencies, but resulted in improved diameter class distribution (DC), with an increase in volume DCs above 35 cm. Continuous Cover Forestry resulted in significantly lower timber production, but with possible ecosystem services that could influence the sustainability of forestry practices. Further research is recommended for the valuation of these ecosystem services, as well as the replication of this study to a wider range of stands, and further economic analysis of the profitability of each of the managements.

Keywords: Forest management, partial cuts, forest models, growth and yield.

1 Introduction

Having been of extreme importance for more than a century, the forestry sector in British Columbia, Canada, contributes to its economical and social development, as well as acting as a source of a variety of benefits to the citizens. The sustainable production and the growth in demand for forest goods and services can contribute to climate change mitigation and the provision of opportunities for the communities [Niquidet and Kan, 2021].

With approximately 60% of its land covered by forests (57 million hectares), of which 22 million hectares (38.8%) are destined for timber harvest activities (Timber Harvesting Land Base - THLB) [Gilani and Innes, 2020], the sector was responsible for 50 thousand jobs in 2020, $4.8 billion in total GDP (Gross Domestic Product) and $11.3 billion exports [Government of Canada, 2022], corresponding to 28.8% of the total province's exports in value [Niquidet and Kan, 2021].

[Gilani and Innes, 2020] define British Columbia as a "unique forest jurisdiction", especially for its diversity in forest typology and rangelands, as well as for the fact that 95% of its land is publicly owned. The remaining 5% of the land (3 million hectares) belongs to nearly 20.000 private forest owners.

In recent years, both climate change and human activities have influenced Canadian forests by an increase in the frequency and intensity of disturbances such as wildfires, drought events, insect infestations and alteration in species ranges [Devisscher et al., 2021], therefore increasing the cost of social-cultural, environmental and economic aspects of rural British Columbia, and consequent permanent closure of sawmills in the region [Breen and Robinson, 2021]. Two of these important disturbances in Canada are the Pine Beetle (*Dendroctonus ponderosae* Hopkins) infestation and the severe wildfires.

Pine Beetle infestation has caused the loss of 723 million cubic meters (53% of the total merchantable volume of pines) [Dhar et al., 2016]) and infested around 18.3 million hectares since the start of the infestation [Corbett et al., 2016], in early 1990. Similarly, forest fires, play an important role in wood availability in the province, since in the last five years, of a long 102 years of fire monitoring data, the three biggest fires were registered in 2017 with

1.2 million hectares, 2018 with 1.3 million hectares, and in 2021 with 0.9 million hectares burned [Ministry of Forests, 2022].

These fires have affected both areas of the THLB and non-THLB. The area burned in 2018 and 2021 corresponded to 8.5 and 5 times the annual average of burned area in the province (158.381 hectares), respectively [Branch, 2019]. For these fires, the proportion of burned area in the timber production area was 58% (700.000 hectares), 23% (300.000 hectares) and 49% (419.500 hectares) in 2017, 2018 and 2021, respectively [Ministry of Forests, 2022], threatening the supply of timber in the long term.

The consequences of the disturbances above mentioned are dependent on forest characteristics such as density, structure and composition. Thinnings can significantly alter these characteristics, and therefore influence in the vulnerability and severity of hazardous events, playing an important role in both, risk management and forest productivity and profitability [Halbritter et al., 2020]. Commercial thinnings (CT) can also generate a diversification in the age structure of the stand and an opportunity for reducing the threats of a timber shortage in areas that are constantly at risk [Griess et al., 2019].

Due to the losses in timber quality resulted from these disturbances, the government of British Columbia determined a strategy called "uplift" from 2005 to 2010, which consisted in increasing the Annual Allowable Cut (AAC) to capture the beetle-affected volume while it was still merchantable [Corbett et al., 2016]. The consequences of the "uplift" strategy in that period were the unbalance and the reduction of the AAC in the following years (after 2010) and a gap in forest growth for commercial purposes that could last until 2060 to 2070 for interior British Columbia [Christian, 2014].

Silvicultural practices could be one of the possibilities to fulfill this gap and provide timber flow during the period of reduced AAC. According to [Christian, 2014], commercial thinnings can provide a variety of benefits, such as: short-term timber availability; an increase in quality and diameter increment; a faster culmination of the remaining stands; and, the capture of natural mortality volume. The capture of natural mortality volume can be defined as the harvest of trees before it dies due to competition and other natural causes. Additionally, it may reduce operational costs per m^3 by increasing the value of forest products, as well as contribute to the resilience of forests regarding biotic and abiotic factors. The redistribution of growing space and resources to the remaining trees is also an additional benefit of thinning interventions, as well as the increase in the complexity and heterogeneity of forest structure [Gauthier et al., 2015], depending on the thinning method.

However, commercial thinnings also present some risks and negative impacts to the forest. [Day et al., 2000] mentions the risk of wind throws as an important factor to be considered and, if possible, mitigated. Additional impacts can be the damage to residual trees that can reach rates of 9% in tree selection management, as well as an increase in the operational cost when compared to the clear-cut alternative (42%) ([Renzie and Han, 2001].

In order to regulate and guide forest managers and companies regarding commercial thinnings, BC Government developed a guideline defining the thresholds and principles to CT practices [MFLNRORD, 2020]. It focus on providing guidance on how, when and if this practice should be applied based on operational experiences and growth and yield model projections. We used this guidelines as a parameter to evaluate the different management regimes and compare the results in timber production over the forest cycle.

Despite the benefits of this practice in forest production, structure and resilience, these benefits are not always captured due to the dependency on the timing of first entry, thinning intensity, pre-harvesting conditions and type of operation [Gauthier et al., 2015]. Due to this uncertainty, many questions regarding this practice have been brought to light in British Columbia.

This research focuses on exploring the effects of different thinning regimes in timber production by changing some parameters such as thinning intensity, frequency and method on a modelling approach. With increasing forest risks and the influence of climate change on the timber supply, we expect to achieve some guidance regarding the selection of the management strategies that will produce enough wood for the timber market in British Columbia, as well as highlight the importance of alternative management strategies to the current clear-cut strategy (Unthinned).

The questions that we will focus on answering in the project are:

1. What are the thinning variables that significantly influences timber production?
2. Which management regimes comply with the Commercial Thinning Guidelines of British Columbia?
3. How can commercial thinnings benefit forest management in British Columbia?

2 Material and Methods

2.1 Area of Study

This study was conducted in interior British Columbia (Canada), more precisely in the Sub-Boreal Spruce (SBS) zone, close to the city of Quesnel, in the Cariboo Regional District (Figure 1). The climate of the region is classified as Dfb (Warm-summer humid continental climate), according to the Köppen-Geiger classification system.

The warm season for the area is of 3.6 months per year (May-September), with daily average temperatures of 20 °C in the summer. The cold season lasts 3.1 months (November to February) and the daily average temperature is below 2 °C in the winter, reaching -10 °C in the coldest months of the year (January) [Spark, 2022].

According to the same source, the average precipitation of the rainy period, which corresponds to 9 months of the year (March to December) is 42 mm, while for the rainless period, 3 months (December to March), is 11 mm. Snowfall plays an important role in the Quesnel region, where the length of the snowy period is 5.3 months, from October to March.

2.2 Stands Selection

A total of 5 stands with similar ages of 30 to 40 years from the last harvest, with different areas, species mix and forest structures were used in the model (Table 1). The plots were harvested (clear cut) in the 70's and 80's, and planted in the following years, although there is no information regarding the initial density and composition of the selected stands.

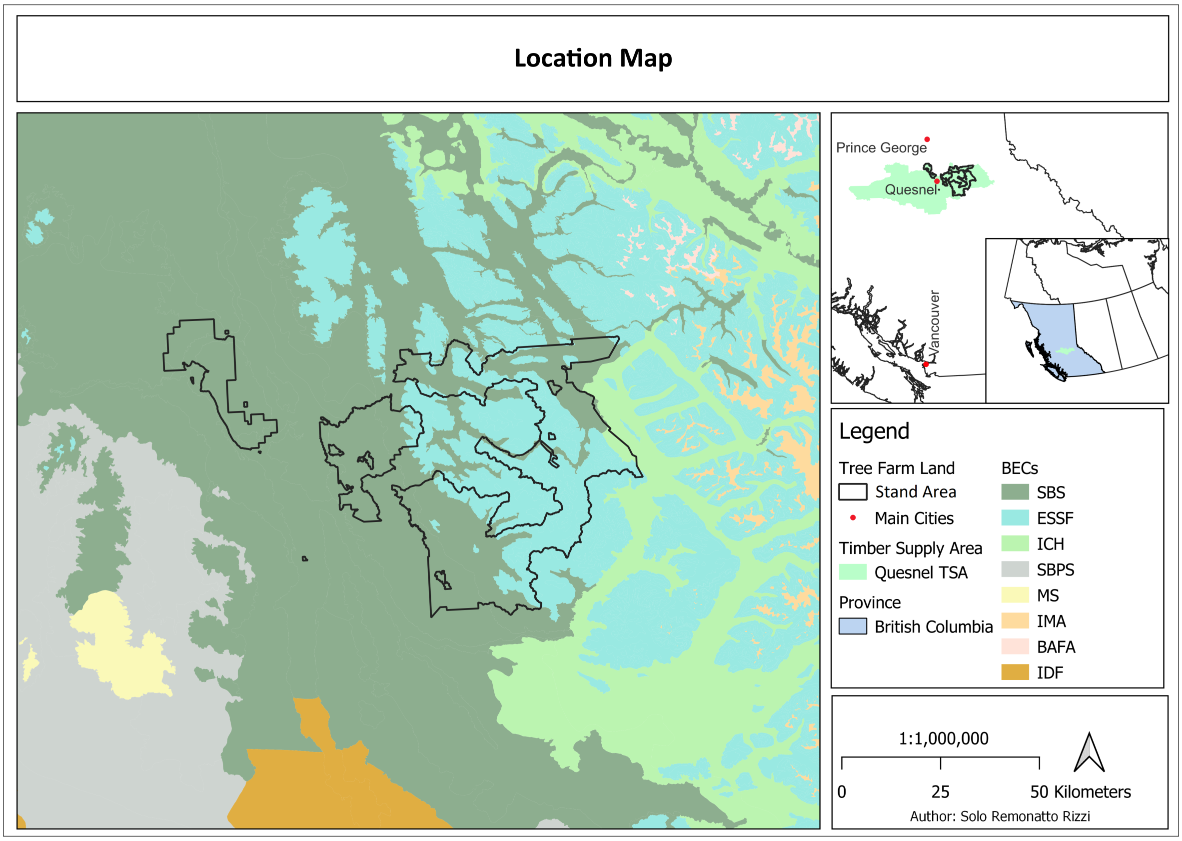

Figure 1: Location map of the area where the stands are in the biogeographic zones of British Columbia. **SBS**: Sub-Boreal Spruce, **ESSF**: Englemann Spruce - Subalpine Fir, **ICH**: Interior Cedar - Hemlock, **SBPS**: Sub-Boreal Pine - Spruce, **MS**: Montane Spruce , **IMA**: Interior Montane - Heather Alpine, **BAFA**: Boreal Altai Fescue Alpine, **IDF**: Interior Douglas-Fir

Table 1: Initial stand characteristics

Stand	Harvest	Dom. Species	Density $(trees/ha)$	BA (m^2/ha)	Volume (m^3/ha)
D2	1983	Lodgepole Pine	1573.8	38.3	245
D3	1983	Lodgepole Pine	1672.2	34.0	220
D5	1983	Interior Spruce	1572.2	34.0	196
D6	1973	Interior Spruce	1924.2	39.0	226
D7	1983	Interior Spruce	1786.4	34.5	202

For each of the stands we collected the density distribution (stems/ha) of all 7 commercial species (Cottonwood, Aspen, Balsam Fir, Birch, Douglas Fir, Lodgepole Pine and Spruce). The distribution was divided into 5 cm diameter classes, which were used as input for the SORTIE-ND modelling software.

As we can observe in Figure 1, the area of this study is located in two main Biogeographic Ecosystem Zones (BEC) of British Columbia: Sub-Boreal Spruce (SBS) and Engelmann Spruce - Subalpine Fir (ESSF). However, since the model is only parametrized for SBS forests, we considered that all the plots are located in this specific zone, specially because we could not obtain the exact plot position in the area.

2.3 Management Regimes

Many different operations and management characteristics can be applied to forests in order to stimulate growth, increase average individual volume, or even achieve different goals, such as increasing biodiversity or changing stand composition, for example. In this study we explored the effects of five of these characteristics in timber production, which can be defined as:

- **Intensity (i):** the amount (%) of basal area removal in each intervention;
- **Frequency (f):** the period in years, between each intervention. High frequency means low values (25 years), while Low frequency means high values (f40);
- **Method:** thinning method, can be from *Above* (removal of the biggest trees) or from *Below* (removal of the smallest trees);
- **Continuous Cover Forestry (CCF):** substitution of the final clear-cut to consecutive thinnings, without removing entirely the vegetation coverage at any point of the forest cycle;
- **Track Distance (t):** the distance between skidding tracks, changing the area in which there will be machinery impacts, and therefore changing the number of trees in the stand.

The total combination for the evaluated scenarios is 192 (4 intensities x 4 frequencies x 2 methods x 2 strategies x 3 harvest tracks). However, we selected only 145 of these thinning regimes scenarios. The removal of 47 scenarios is because the alternative of continuous forest cover with thinning from below would generate big trees that would not be removed at the end of the cycle without the clear cut, and therefore would not result in an interesting and applicable result for timber production, which is one of the goals of this study. The summary of the values for each parameter is exposed in Table 2.

Table 2: Parameters used in the simulations

Parameter	Values			
Intensity (m^2/ha)	25	30	40	45
Frequency (years)	25	30	35	40
Track Distance (m)	20	32	40	
Method	Below		Above	
Strategy	CCF		Clear Cut	

The significance of each of the above mentioned regime parameters were evaluated by performing a Variance Analysis (ANOVA). This allowed us to understand which of the factors actually influences timber production and to simplify the analysis by disconsidering insignificant factors from the final results.

When including a final harvest in the simulation, the partial cuts were added systematically based on the defined frequency, and a final clear cut was added at the end of the rotation. In order to add this final intervention, we calculated the time difference between the last thinning and the final clear-cut. If the difference is lower than 15 years (Equation 1), instead of adding the thinning intervention, we applied only the final clear cut at the end of the rotation. This was made to avoid two interventions in a short period of time, which would not allow the forest to grow enough to compensate for the impacts and costs of the harvesting operations.

$$
\begin{aligned}
ifIntervention <= FinalHarvest - 15 \\
thenIntervention = FinalHarvest \\
elseIntervention = Intervention
\end{aligned} \tag{1}
$$

Because of the complete removal of vegetation cover, clear cuts can produce some negative impacts, such as contribute to soil erosion, increase water run-off and destruction of wildlife habitats, both during and after harvesting operations. Therefore we adopted an option to try to reduce these impacts by promoting continuous forest cover, which consists in avoiding the clear-cut at the end of the forest cycle and applying only thinnings during the full rotation of the forest.

Additionally, we considered different distances between tracks that represents the paths of the skidders when removing the wood from the stands. We tried to evaluate if there was a significant change in timber production and tree growth by changing the distance of the tracks (Figure 2).

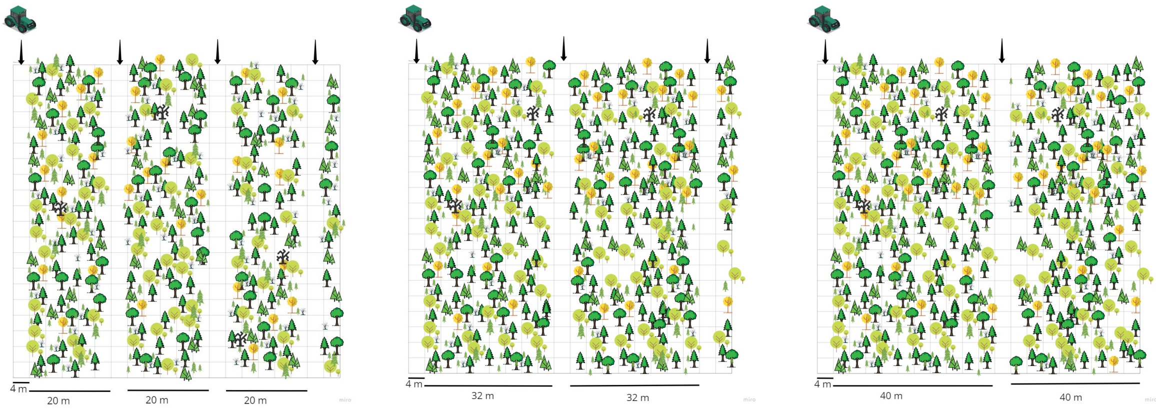

Figure 2: Scheme of the different skidding track distances. From left to right: 20, 32 and 40 meters distance between tracks.

2.4 The Model - SORTIE-ND

Because of its flexibility and the ability to simulate mixed stands, we opted to use SORTIE-ND for the simulations. Similar to TASS (Tree & Stand Simulator) used by the government, SORTIE is an individual tree, spatially explicit (distance dependent) forest dynamics model. It was developed in the 1990's by a group of researchers guided by Canham and Pacala [Pacala et al., 1993], followed by significant changes done by Dave Coates in the early 2000's [Coates et al., 2003]. It consists of empirical and mechanistic behaviours, incorporating horizontal and vertical structures of the forest. In the model, juvenile growth is based on the availability of light for each tree of the stand, and therefore it accounts for the impacts and effects of the interaction between trees, and the heterogeneity of the environment. While adult growth is modelled as a result of different functions of penalizations over the maximum increment (Potential), as shown in the Equation 2 below:

$$NCIGrowth = Potential * Shading * Crowding * Neighbour * Size \tag{2}$$

We used SORTIE-ND version 7.05.07 primarily to define the behaviours that were included in the model, as well as the different distances between skid tracks (distances of 20, 32 and 40 meters), exemplified in Figure 2. These files containing the sets of behaviours are called parameter files.

In the main parameter files, we defined the base information that was applied for every stand and management regimes, such as the forest cycle (simulation length) by 100 years (time steps), the size of the simulation plot by 216 x 200 meters (4.32 hectares), and the different patterns of skid tracks.

The utilization of RStudio and the *rsortie* package, available as a GitHub repository in (https://github.com/aclason/rsortie.git), allowed us to generate all the 725 parameter files that were used to obtain the results (145 management regimes x 5 stands). The logic behind the parameter files consists in applying systematically the interventions over the forest cycle. In the case of continuous forest cover, there is no clear cut at the end, and therefore we only applied the thinning regimes in the stands for the total length of the simulations.

The behaviours can be defined as the events in the forest cycle that determine the main demographic processes: tree growth, regeneration, as well as other forest disturbances, such as harvesting, pests and windthrows. The original behaviours applied in this study, such as growth, regeneration, allometry equations and mortality parameters and values were maintained from the original parameter file available for British Columbia's SBS forests, obtained from Bulkley Valley Research Centre (BVRC). These equations were calibrated using a consistent dataset collected from BC's forests that were used to predict the different coefficients [Canham et al., 2004], [Wright et al., 2000] and [Astrup et al., 2007]

For the management alternatives, we simulated the different thinning characteristics, explained in Table 2. The regimes consisted in modifying the defined intensity and frequency of the interventions, the method, and also the possibility to apply a continuous forest cover management alternative.

For this study, the intensity was set in a way that, for the first intervention in the cycle, the removal of the basal area from the thinning would be compensated by the opening of the skid tracks (clear cut), defined in Equation 3.

$$\begin{aligned} ccIntensity &= 100/(HarvestTrack/4) + 1 \\ FirstThinIntensity &= Intensity - ccIntensity \end{aligned} \tag{3}$$

SORTIE-ND also includes some stochastic behaviours in its processing, such as the spatial allocation of the trees, regeneration and mortality. Therefore, we processed each of the 725 parameter files three times. In total, we will analyse 725 x 3 = 2175 parameter files. To do that more practically and automatically, we created 5 batches of files based on the stands. Each batch contains the 145 parameter files for the stand that will be repeated 3 times.

The resulting text files corresponds to the tree list in each of the time steps of the simulation, accounting for 217.500 files (2175 parameter files x 100 time-steps), which were then added to the R Studio environment, summarised by diameter classes and further processed to obtain the results.

2.5 Commercial Thinning and Forest Management

The government of British Columbia has defined a set of requirements regarding the application of commercial thinnings in their forests. In order to evaluate the efficiency and success of the different thinning regimes simulated in this study, we took into consideration these requirements and thresholds in our analysis. There are 3 main conditions defined by [MFLNRORD, 2020]:

- **Stand Retention**: commercial thinnings contribute to the growth of the forest through the increase in the availability of light, space and resources. The Commercial Thinning Guideline of British Columbia establishes a minimum Basal Area (BA) retention of 20 m^2/ha to guarantee its forests' potential productivity during the entire forest cycle;

- **Volume Removal**: the first intervention in a forest represents a significant investment, especially when considering the necessity of building roads and other infrastructure. Along with the investment costs, there is an increase in operational expenses due to higher levels of difficulty and consequent reduction in productivity of forestry operations in the stand, such as harvesting and skidding. Aiming to reduce the total cost of this operation, the guideline recommends the harvesting of a minimum of 50 m^3/ha of merchantable timber that should be sold and contribute to a positive input in the cash flow. Merchantable wood is defined as timber from any of the commercial species with a Diameter at Breast Height (DBH) above 12.5 centimetres;

- **Total Rotation Volume**: total timber production at the end of the cycle of the thinned stands should be superior to 95% of the unthinned volume production. The guideline also defines two thinning priorities: a positive yield, which refers to a ratio bigger than 1.05 of the unthinned total volume; and, a neutral yield, when the cumulative volume is between 0.95 and 1.05 of the unthinned volume.

3 Results

3.1 Stochastic variation across repetitions in SORTIE-ND

As mentioned before, some of the behaviours and processes embedded in SORTIE have certain randomnesses involved, such as the position of the trees in the grid, tree mortality and regeneration. In order to understand and evaluate if this stochasticity had a significant influence on the simulation's results, we processed each of the regimes three times. We obtained an average variance from the repetitions in the magnitude of 0.347 %, or 2.128 m^3/ha in the total timber production at the end of the forest cycle. More detailed information can be found in Appendix A, where we present a plot with the variance for each of the managements for all the stands.

In general, all the stands had similar results. Managements containing thinnings from below and with final clear cut had more variability, and the only management regimes that had coefficient of variation higher than 1%. Most of the regimes containing thinnings from above had a lower variance for both continuous cover and final clear cut. For the unthinned managements, the variance was different for each stand, but close to the mean variance.

For the majority of the simulations, the variance was below 1% of the mean, except for the managements and stands presented in Table 3. Of all the 725 simulations, only 12 of them resulted in variances above 1%. Stand D2 was the one with the highest variance between the stands, and there was no pattern found for the management regimes. Even for these situations, the difference in total volume produced at the end of the rotation was lower than 2%, with the maximum difference of 9.24 m^3/ha at the end of the cycle for stand D2, for example.

Table 3: Simulations with high variance between repetitions.

Stand	Management	Mean_Vol	SD_Vol	CV_Vol (%)
D2	t20-f25-i25-Below-Clear	597.34	9.24	1.55
D2	t20-f30-i45-Below-Clear	563.65	6.35	1.13
D2	t20-f35-i40-Below-Clear	571.20	8.86	1.55
D2	t20-f40-i40-Below-Clear	588.60	7.58	1.29
D2	t40-f35-i25-Below-Clear	590.93	6.63	1.12
D2	t40-f35-i40-Below-Clear	564.94	5.77	1.02
D3	t20-f30-i25-Below-Clear	632.37	6.56	1.04
D3	t32-f30-i25-Below-Clear	626.95	6.28	1.00
D3	t32-f35-i40-Below-Clear	606.58	6.44	1.06
D3	t40-f30-i40-Below-Clear	604.52	6.12	1.01
D5	t20-f30-i25-Below-Clear	625.72	7.29	1.16
D6	t32-f25-i30-Below-Clear	637.47	7.84	1.23

Since the variance was not of huge difference between the three repetitions, we decided to calculate the average between these repetitions to facilitate the data processing. Therefore, for this step onwards, we considered only one repetition for each of the 725 simulations.

3.2 Which factors influence timber production?

In this study we evaluated the influence of 5 operational and silvicultural factors (track distance, frequency, intensity, method and CCF), expecting to observe a difference in timber production at the end of the forest cycle for each and all of the combinations. However, which of these factors have an actual influence on timber production?

By performing an ANOVA analysis, we concluded that almost all of the factors were significant ($p < 0.1$) for timber production, with only one exception. Table 4 shows the result of the Two-ways ANOVA test, where we can see that the distance between skidding trails (track) confirms the null hypothesis (H_0), and therefore it does not influence the final timber production of the forest.

Table 4: ANOVA Table

	Df	Sum Sq	Mean Sq	F value	Pr ($>F$)	Significance
track	2	3412.56	1706.28	0.79	0.4529	
frequency	3	752257.02	250752.34	116.44	0.0000	***
intensity	3	1301354.58	433784.86	201.43	0.0000	***
method	1	21715.85	21715.85	10.08	0.0015	**
cover	1	18651689.21	18651689.21	8660.92	0.0000	***
Residuals	2149	4627969.54	2153.55			

Aiming to simplify data processing and the analysis of the results, we excluded this factor from the management combination by calculating the average of the results of the three different track distances evaluated in this project (20, 32 and 40 meters). With this reduction, we ended up with only 49 management regimes (4 intensities x 4 frequencies x 2 methods x 1.5 CCF + 1 unthinned).

3.3 Forest Management Results

3.3.1 Live Basal Area - Retention

We evaluated the basal area of all the stands for the 49 managements for the duration of a forest cycle of 130 years. Figure 3 shows the BA range (lower and upper limit) for all the stands and regime combinations. The overlapping of the managements with thinning from above, both with continuous forest cover (CCF) and with final clear cut (Clear) was expected since the only difference between these two managements is the final clear cut at age 120.

The thinning regimes below were the ones that presented the lowest basal area after the interventions. For this method, the guideline condition was violated in three situations. Management f25-i45-Below-Clear did not fulfil the BA condition after the second intervention (19.2 m^2/ha), while managements f30-i45-Below-Clear (18.6 m^2/ha) and f35-i45-Below-Clear (19.5 m^2/ha), violated this condition after the third intervention.

The residual basal area for managements from below and with intensities higher than 40% resulted in a basal area lower than the initial value of the stand (age 31). A reduction is also recorded for high frequencies (f25 to f35). The exceptions occur in frequency f40, where, despite registering a decrease compared to previous interventions, the BA at age 120 is still above the initial BA limit (black dashed line).

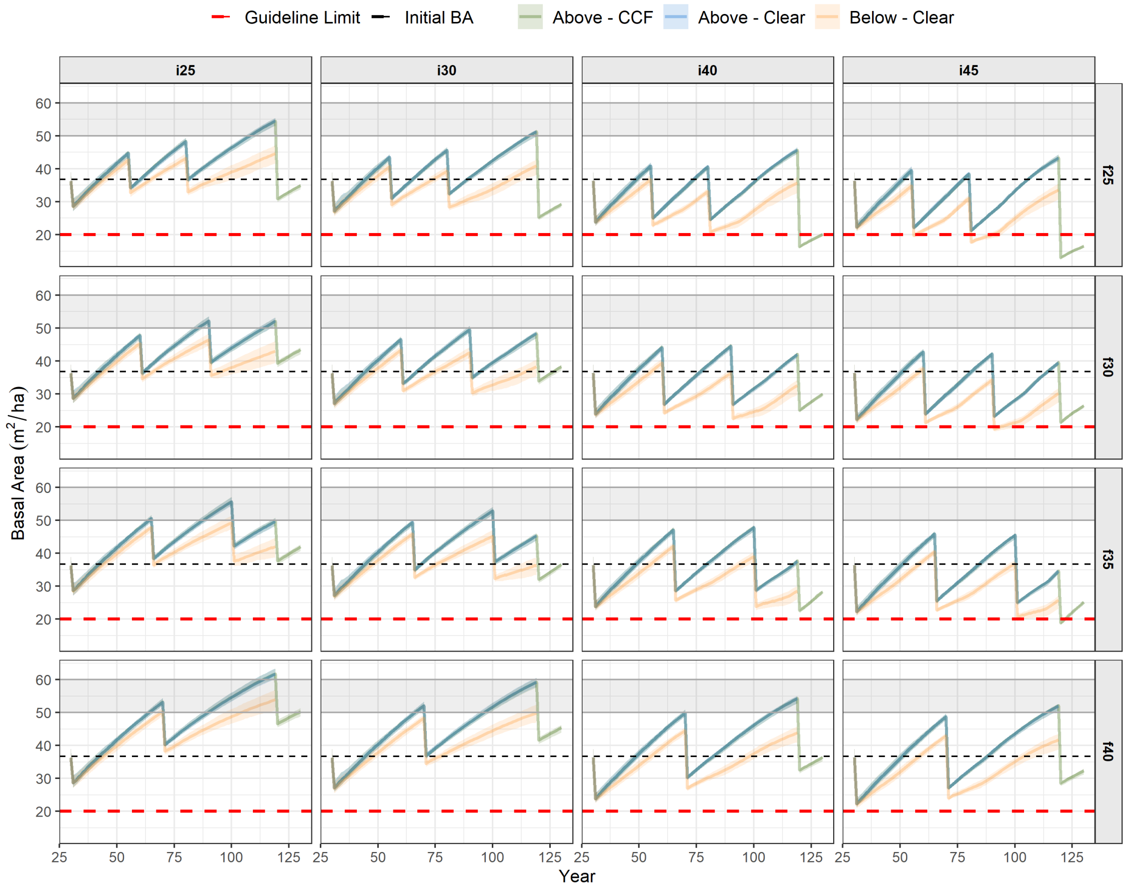

Figure 3: Live Basal Area (m^2/ha) over the forest cycle. **Grey area:** 50-60 m^2/ha range, **Red Dashed Line:** minimum of 20 m^2/ha defined in the Commercial Thinning Guideline, **Black Dashed Line:** initial stand basal area

All the regimes from above (removal of the biggest trees) resulted in higher basal area retention, and also higher BA at the time of each intervention when compared to thinnings from below. The BA retention difference, after harvesting, between methods (blue - yellow lines) increases after every intervention along the forest cycle, ranging from 2 m^2/ha in intervention one to 4 m^2/ha in the last harvesting.

For the BA at the time of each intervention, in the first thinning, the gap (blue - yellow lines) is 2 m^2/ha, while for the last intervention (before clear cut) it is 9 m^2/ha. This increase in BA retention results in the managements Above-Clear compliance to the limit of 20 m^2/ha.

This result was slightly different when considering the continuous cover strategy. In this case, since we do not have the final clear cut, the basal area retention limit could have been violated with another thinning intervention instead of the final clear cut at age 120. We observed this situation for three managements: f25-i40-Above-CCF (16 m^2/ha); f25-i45-Above-CCF (13 m^2/ha); and f35-i45-Above-CCF (19.8 m^2/ha).

An equilibrium appears to be reached in two situations. The first one is in between managements f30-i30-Above and f30-i40-Above, for both clear and CCF regimes, which shows similar BA apexes and bases at the time of the interventions. The second situation is for frequency f40 and intensity i45, in the last row of Figure 3.

The variation between stands, which can be observed by the size of the envelopes, is higher for managements from below and with a final clear cut (yellow line), when compared to the other two combinations. Especially in this situation, the variability between stands grows in the direction of the age of the forest, reaching the highest variance (around 5 m^2/ha) at the end of the forest cycle. Therefore, we can say that managements from below are more susceptible to the initial characteristics of the stands.

3.3.2 Volume Harvested per Intervention

All the stands presented similar results when considering the timber production at each intervention. For demonstration purposes, we will utilize stand D6 as an example, but all the graphs for the other stands are included in Appendix B.

Figure 4 shows that for all the managements from below (yellow), there was insufficient harvested volume in intervention one, even in the higher intensities (i45), where the maximum harvested volume was 41 m^3/ha. The exceptions are stand D2 which achieved the minimum mark (red dashed line) for intensities i40 (56 m^3/ha) and i45 (64 m^3/ha), and stand D5, which reached the minimum threshold only for the highest intensity (i45), with 52 m^3/ha.

All the other managements alternatives achieved the minimum timber production in all the situations, even for the smallest intensity (25% basal area removal), with a minimum of 62 m^3/ha. The combinations that produced more timber in each intervention are, in decreasing order: Above-Clear, Above-CCF and Below-Clear.

The only exception in which this pattern is not respected is for stand D6. In this case, managements from below can produce more timber in the last intervention than in thinnings from above, which are the cases of managements: f30-i25 (423.8 against 413.4 m^3/ha), f35-i25 (412.8 against 392.4 m^3/ha), f40-i25 (506.0 against 493.7 m^3/ha), and f35-i30 (366.6 against 356.0m^3/ha). This could be explained by the fact that stand D6 is the stand with the highest tree density (1924.2 stems/ha) and initial basal area (39 m^2/ha). It means that in previous interventions, the BA removal was achieved earlier, leaving more trees in the stand for the final intervention.

In all the situations for the lower intensities (25% and 30%), the managements with clear cut (yellow and green lines) had higher cumulative timber production when compared to CCF (blue) and the unthinned management (black dashed line). For the higher intensities (40% and 45%), all the alternatives with thinning from below were under the unthinned timber production reference.

For the continuous cover alternative (blue) the cumulative timber volume was higher than the unthinned reference only for the management f25-i45, with 7.1 m^3/ha above this threshold. Additionally, only in three situations the total volume produced from continuous cover was higher than thinning from below: f25-i40 (60.2 m^3/ha higher), f30-i45 (30.2 m^3/ha higher) and f35-i45 (30.8 m^3/ha higher).

Figure 4: Timber harvested in each intervention for stand D6. Semi-transparent columns represents the live timber stock, while the solid columns represents the harvested volume of the stand. The lines shows the cumulative harvested timber volume over the forest cycle. The black dashed line is the volume produced in the unthinned management.

The increase in intensity results in a reduction in timber stock (background columns) at the final intervention. The reductions are of the magnitude of 7% (from i25 to i30), 15% (from i30 to i40) and 9% (from i40 to i45). Regarding the frequency influence in timber stock, there is also a reduction of around 7% for all frequency intervals, with exception of frequency f40, which because of the lower number of interventions, resulted in an increase of around 25% compared to frequency f25.

3.3.3 Total Volume Harvested

As mentioned before, for all the managements with thinning from above, the cumulative volume was higher than the unthinned management. For these situations, the difference between unthinned and thinned total volume harvested increases in the direction of the lowest to highest frequencies (f40 to f25), and lowest to highest intensities (i25 to i45), as we can see in Figure 5. Therefore, the maximum increment when comparing the control management was found in management f25-i45-Above-Clear, reaching values that range from 1.16 for stand D7 and 1.29 for stand D6. For the lowest increment of the above managements (f40-i25), we can register ratios from 1.1 for stands D3 and D5 to 1.7 for stand D6. In both cases, inside the positive yield threshold (¿ 1.05).

Alternatively, for the managements from below, the direction of the increment is from higher to lower frequencies (f25 to f40) and from higher to lower intensities (i45 to i25), which can be seen by the colour strength of the cells in Figure 5. In this case, only a few managements were below the neutral yield priority, but no lower than 0.92, having significant differences between stands. The best results for the thinning from below range from 1 to 1.12, with the highest values found for stand D6 and D7 and management f40-i25.

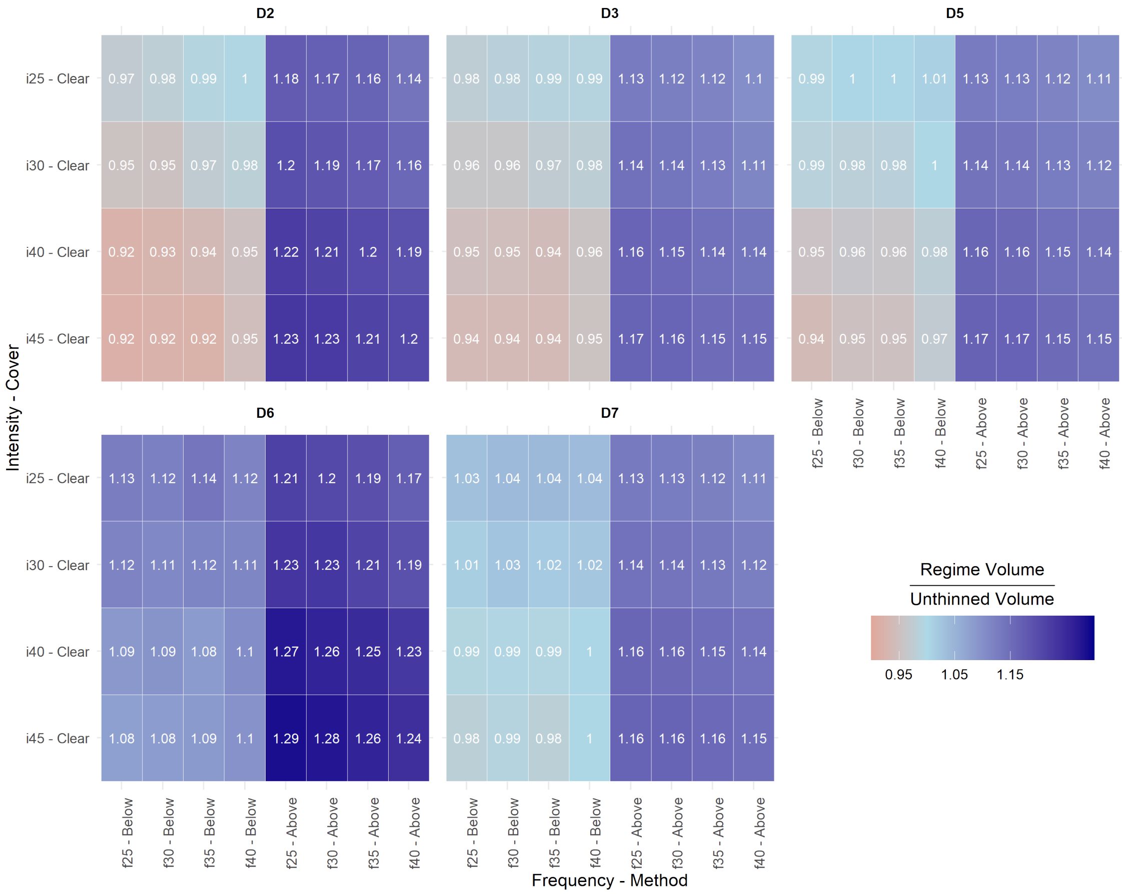

Figure 5: Relative forest productivity for each management compared to the clear cut. The darker the blue, the higher the relation between regime volume and unthinned volume, while the reedier the color, the lowest is this relation.

Continuous cover management (CCF) was much less productive (Figure 6) than clear managements, since the harvested volume is significantly lower, especially in the last intervention. In this graph we did not account for the remaining growing stock at the end of the rotation, which can be seen in Figure 7 as total live volume (m^3/ha) at age 120, and the increase or decrease from the initial stand volume (in %).

Similarly to what was found for the thinning from above with clear cut, the increment for continuous cover strategy increases from low to high frequencies (f40 to f25) and from low to high intensities (i25 to i45). The highest values were found for management f25-i45, ranging from 1.02 (stands D3, D5 and D7), to 1.13 for stand D6.

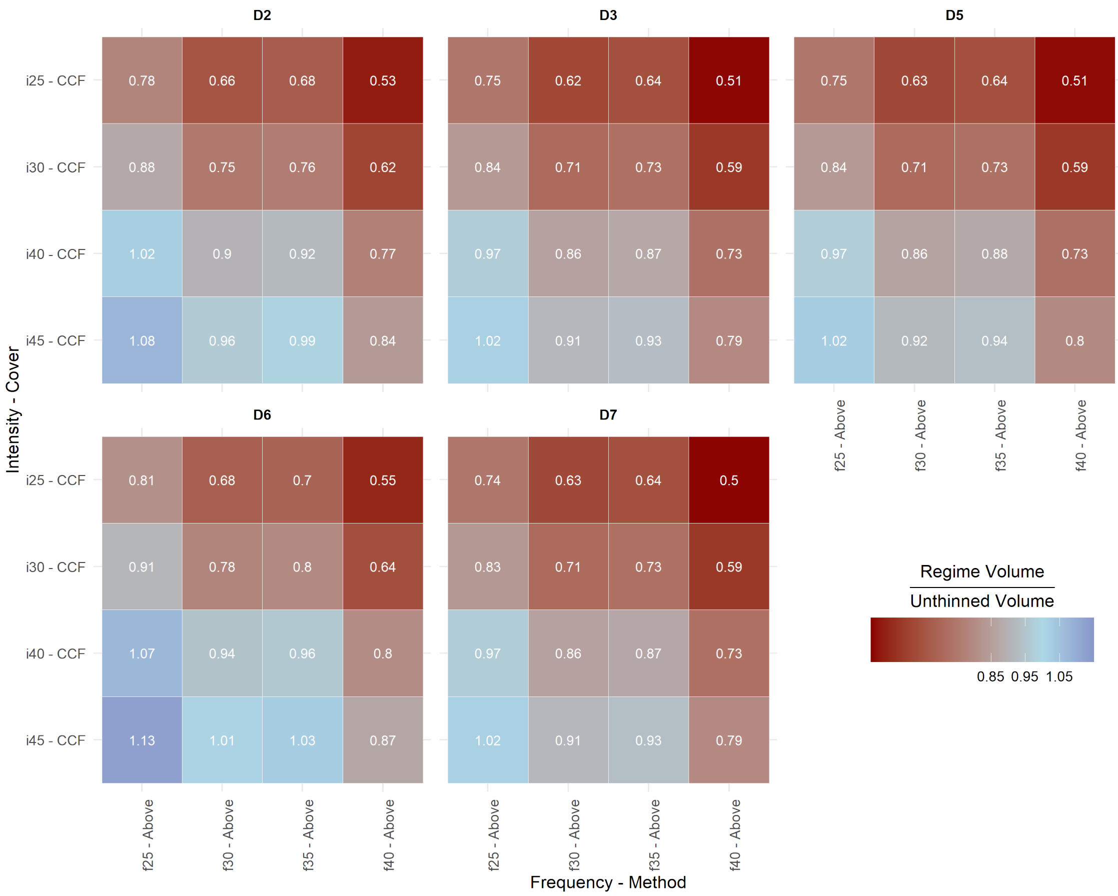

Figure 6: Relative forest productivity for each management compared to the clear cut. The darker the blue, the higher the relation between regime volume and unthinned volume, while the reedier the color, the lowest is this relation.

However, despite the significant reduction in productivity considering this strategy, we also need to assess the livestock after all the interventions (Figure 7). Logically, with increasing total removal (high frequency and high intensity), the standing volume will be lower when compared to the opposite situation.

The edges of the plots in Figure 6 either represent excessive remaining live volume (top/right) or excessive volume removal (bottom/left). However, when considering the middle managements we can achieve a certain balance in both volumes (harvested and stock).

For managements f30-i30 and f35-i30 the total volume production was only around 75% of the unthinned management, but the livestock has slightly increased from the initial stand volume. For stands D2 and D6, where harvesting was between 75% and 80%, the stock volume increment ranged from 11 to 17% from the initial stand volumes. However, with lower harvesting (between 70% and 75%), the livestock grew between 27% for stand D3 and around 35% for stand D5, showing a clear dependency on the initial conditions of the stand for stock management. In general, if the volume removal is between 80% and 90% of the unthinned harvested volume, we can observe a reduction in the stock of 10% to 20% from the initial stand volume.

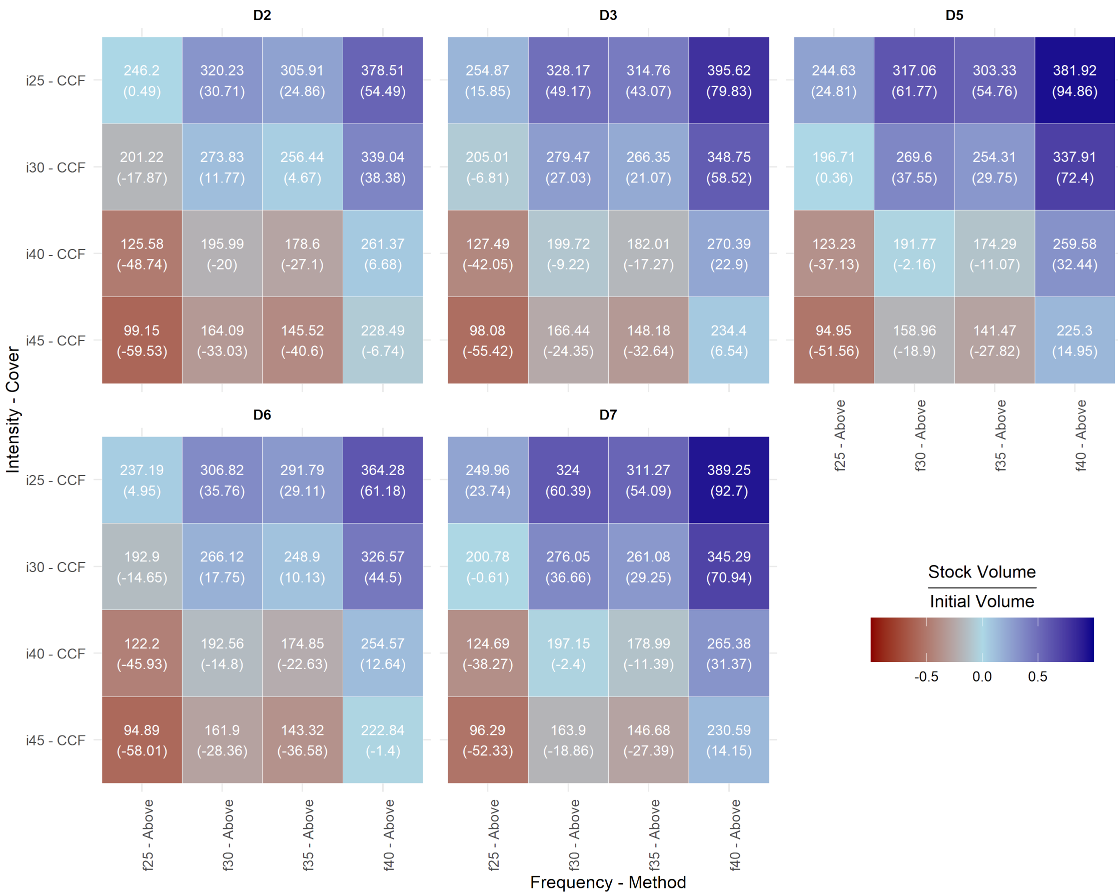

Figure 7: Relative forest productivity for each management compared to the clear cut. The darker the blue, the higher the relation between stock volume and initial stand volume, while the reedier the color, the lowest is this relation.

3.3.4 Diameter Class Distribution

Different forest managements can also result in forest structure changes. One of the benefits of commercial thinnings is the diameter increment of the remaining trees. To identify these changes, we analysed the density (Figure 8) and volume (Figure 9) of the living trees at age 110, divided into 5-centimeter diameter classes (DC). Once again, we used stand D6 as an example, while the graphs for the other stands can be found in Appendix C.

The managements from above (top 4 rows of the facet) have similar diameter distributions compared to the unthinned management. One of the differences is the reduction of the number of trees in all diameter classes, with exception of diameter class 25-30 cm which remains constant for intensities i25 and i30, regardless of the frequency (around 350 trees/ha). The only increase in tree density happens in initial DCs, indicating the appearance of regeneration. The regeneration increases with the increase in intensity (from 68.6 to 503.9 trees/ha for frequency f25) and reduces with the decrease in frequency, reaching its minimum in f40 (from 36.5 to 173.5 trees/ha).

For thinnings from above, the number of trees in higher diameter classes (over 30 cm) does not change crucially with the increase in intensity. The classes that had the highest reduction are 15-20 and 20-25 for all the frequencies, reaching their lowest values for intensity 45%. When considering frequency, the opposite happens with the decrease in frequency. There is an increase in tree density in these DCs for lower frequencies, due to the higher time for the forest to grow.

There is a maintenance of the same tree frequency for higher diameter classes (¿ 25 cm), but a reduction in the middle DCs (15-25 cm). Additionally, the regeneration (lower diameter classes) is benefited by higher intensities. This can be observed by the increase in several trees in the lower diameter classes, especially class 5-10 cm and 10-15 cm, when compared to the unthinned management.

Similarly to the thinning from above, thinnings from below resulted in increased regeneration for higher intensities, resulting in more than 600 trees/ha in DC 5-10 for f25-i40, for example. Two important differences can be observed: the removal of nearly all of the trees from middle and lower DCs (10-30 cm); and, a small increase (52.7 to 107 trees/ha, depending on the frequency and intensity) for the diameter classes that did not account for almost any tree in other managements (35-50 cm), especially for lower frequencies and lower intensities.

Figure 8: Density Distribution per Diameter Class for stand D6. The grey columns represents the density over diameter distribution on the Unthinned management. Different colors means different diameter classes.

Even though the total number of trees in the stand has been reduced, the increase in the number of trees in higher DCs has resulted in an improvement in volume production for each of these diameter classes (Figure 9). For the lower diameter classes, despite the abundance of trees, there are no significant changes in the volume, since these trees are of very small diameters and, probably, heights.

However, when considering higher diameter classes, especially the ones that for other managements alternatives were not abundant, the increase in volume is of great importance for adding value to the final product.

Thinnings from above shows volume distributions similar to the unthinned management, following a close to normal distribution. For thinnings from below, with increasing in intensity (from i25 to i45), despite having a reduction in tree count, there is an increase in volume for all the higher classes. For example, when considering f40-i25, we have that the most productive DC is 30-35 cm (189.7 m^3/ha), while for f40-i45, the most productive diameter class is 40-45 cm (166.3 m^3/ha).

A similar result can be found for lower frequencies as well, with the difference that, for management f25-i25, the most productive of the high diameter classes is 35-40 cm (197.4 m^3/ha), and for f25-i45, 45-50 cm (137.9 m^3/ha), one class further when compared to a lower frequency. Additionally, we can see that, for frequencies f25 to f35, the most abundant diameter classes are one DC above f40. This means a swift of one diameter class when compared to the lower frequency (f40), and therefore more valuable wood is expected in these managements.

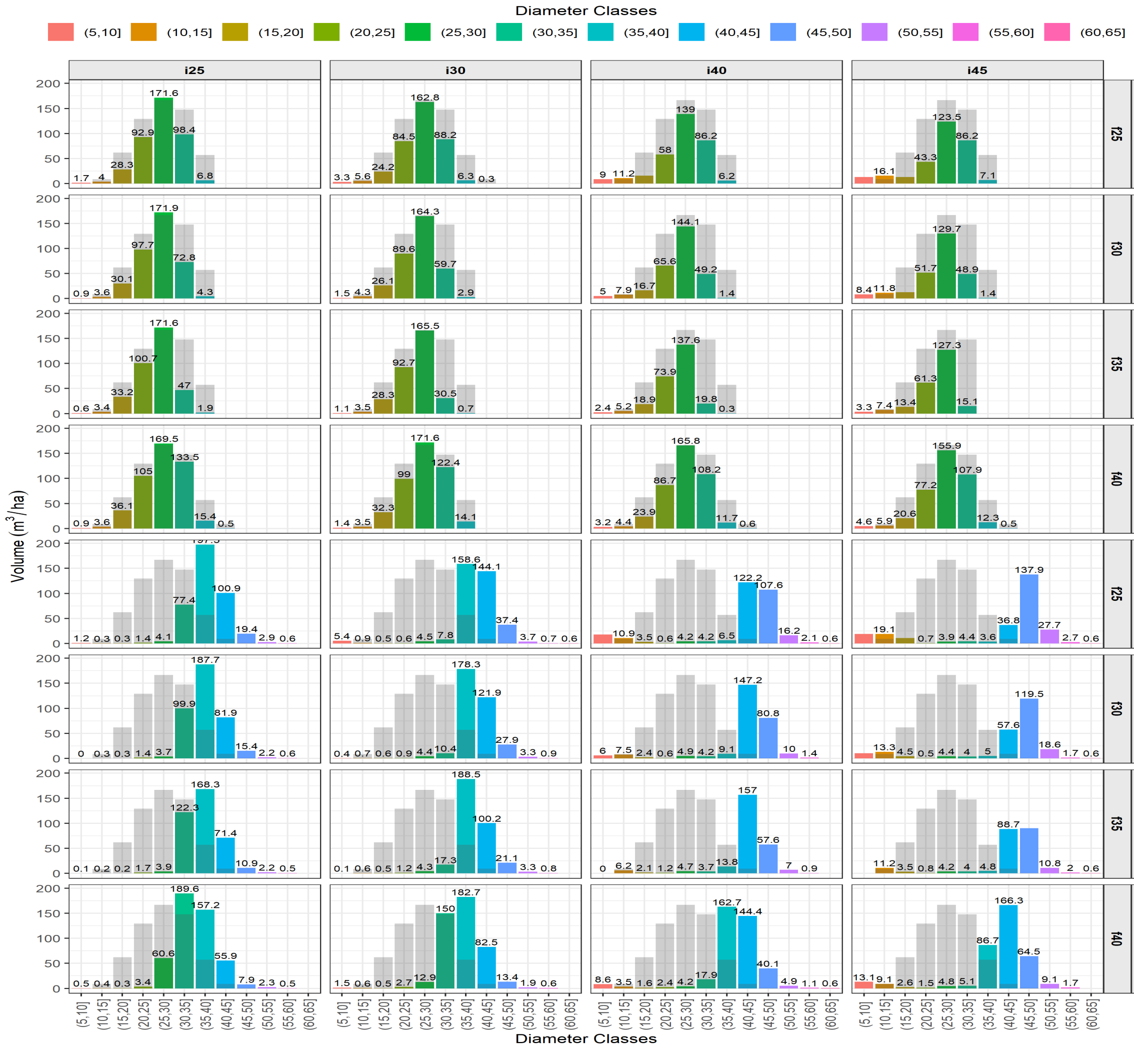

Figure 9: Volume Distribution per Diameter Class for stand D6. The grey columns represents total volume over the diameter distribution on the Unthinned management. Different colors means different diameter classes.

4 Discussion

4.1 Modelling Approach

Simulating forest managements and its effects on tree growth can assist foresters to determine the best scenario for a specific future goal. The advantages of the model used in this study, SORTIE-ND, are the capability of simulating mixed stands growth and yield based on neighbourhood dynamics, as well as the flexibility to adjust and configure the desired behaviours to be considered in the modelling process.

This model has been used in Spain, Puerto Rico, New Zealand and, of course, Canada. In British Columbia since the early 2000's it was used by many different researchers in a variety of fields, especially to determine the effects of Mountain Pine Beetle (MPB) infestation in the forest ([Hawkins et al., 2012]), other disturbances ([Nitschke et al., 2012]), and specific tree species regeneration ([Vanhellemont et al., 2011]).

However, to this date, there was no study found utilizing this software to analyse commercial thinning regimes for timber production at a stand level in British Columbia. Similar studies were conducted on a landscape level ([Griess et al., 2019]), and at a stand level in other countries, especially in Spain ([Ameztegui et al., 2017], [Morán-Ordóñez et al., 2020], and [Diana Simon and Ameztegui, Aitor, 2021]).

The lack of application of this specific model in commercial thinning studies in the province can also be explained by competitor models, which is the case of TASS (Tree & Stand Simulator) which is often and more commonly used for forest growth and timber production predictions in British Columbia.

We aimed to evaluate the outcomes in final timber production under different thinning regimes to understand what are the current forest management possibilities that could contribute to timber production. By evaluating the variance of the model runs, we were able to conclude that there was no significant difference in total volume between runs (maximum of 1.55%), and therefore stochasticity did not play an important role in our study, although present in some of the model behaviours.

Due to the flexibility of SORTIE-ND, the initial idea of this study was to assess the production of different ecosystem services, in addition to timber production. However, because of the complexity and number of different scenarios, this approach was not able to be conducted. Limitations in models to determine these different ecosystem services in the province were found, although it would be recommended for future studies. Assessing these ecosystem services would contribute to determine not only the most productive, but also the most sustainable and resilient management. Some of the services that could have been assessed in this study are forest fuel for the fire, wildlife habitat diversity, soil conservation and pest infestations.

Also, other forest parameters could have been studied in these simulations that would contribute to a better understanding of the behaviour of forests in British Columbia, such as tree mortality, regeneration and also the stand composition transition for the different environments created after each of the commercial thinning interventions.

4.2 Commercial Thinning Guidelines

Despite not being a common practice, commercial thinnings have been studied as a short and mid-term solution for timber provision in the province, especially after MPB infestations and the severity of fire events. There is a government guide for this operation developed in 1999 that regulates the conditions, effects and applicability of this practice in British Columbia ([British Columbia. Forest Practices Branch, 1999]). Further studies were developed by FP Innovations ([Pavel et al., 2021]) and other government agencies ([MFLNRORD, 2020]). This last document establishes all the thresholds and parameters that we used for the analysis of the success of the regime.

We identified that the most important factors that influence timber production are frequency, intensity and method. The distance between tracks was analysed but did not play an important role in defining total timber production. We believe that the influence of skid tracks would be present in a more operational context, since the productivity of the machines, fuel consumption, and wood stock distributions in the stand could modify operational planning and the operation itself. In this context, higher distances should result in higher machinery productivity and reduced operational cost [Cabral et al., 2020].

Additionally to operational costs, the impacts on soil and water conservation, cultural heritage, wildlife habitats, and other environmental and social consequences that machinery causes during operations should be considered [Pavel et al., 2021]. In that thought, after choosing the right management alternative, these conditions should be evaluated to achieve the best results from the forest with the lowest cost and operational impact possible.

Thinnings from above resulted in enough basal area retention. This could be explained by the removal of fewer trees that would suffice for the BA removal rate, and therefore, the retention of more, although smaller, trees in the stand. A study evaluating tree growth and MPB infestations was conducted by [In and Johnstone, 2002], where he found that BA accumulation is faster in thinned stands and that heaviest thinnings (40 to 60%) resulted in growth rates as high as pre-infestation.

We also found that the majority of the regimes analysed complied with the Commercial Thinning Guidelines, in BA retention and intermediate and final timber production. A few exceptions were found, but it is safe to say that these alternatives are efficient and a possible solution for timber production, and should be applied whenever legal and technical conditions are favourable [Griess et al., 2019].

There were substantial variations in the indexes utilized for the 5 stands evaluated, showing a dependency, not only from the thinning regime characteristics, but also from the initial conditions of the stands. Stands with higher initial tree density resulted in more flexible stands. That is, not many, or almost none of the regimes crossed the thresholds for the Guidelines in these situations (stand D6 for example). Regarding timber production, dominant species did not play an important role, however, when considering regeneration, mortality and other parameters, these characteristics might be of great importance to the resilience of the stand.

4.3 Effects of Commercial Thinnings in Timber Production

Production of timber is one of, but not the only, main outcomes of forest management. Many different strategies can be used to favour one specific product production, ecosystem services or any other management objective. Timber production can have different approaches, for example, focusing on the total stand production, for processed products or bioenergy, or improving individual volume, for the production of lumber.

It is important to highlight that the results of the BA retention in this study represent the minimum value over all the stands. Therefore, it might be that, for some stands, even for the managements that recorded lower values, the BA retention can be above the limit defined by the government. This study focus not to evaluate a specific stand growth, but to identify trends and limits of the management regimes, therefore, we did not differentiate the stands in this first analysis.

4.3.1 Thinning from Below

We found that by removing trees from below, the volume harvested in the first intervention, at age 31, was not enough to produce the minimum volume determined in the CT Guidelines (50 m^3/ha). A delay in the first thinning intervention could be suggested in this case. Although [Jaakkola et al., 2006] found that delaying thinning reduces the increment in Basal Area in Finland. Also, the author found that delaying the CT intervention does not influence in the total profitability of the stand (Net Present Value - NPV), but low-intensity thinnings with delayed intervention can contribute to maximum standing merchantable volume.

Our results for some stands and thinnings from below also corroborate with the findings in many other studies where the gross volume production was lower than the control (unthinned) scenario [Christian, 2014]), but with a significant increase in in the average DBH of the stand (Figure 9).

Similar to a study conducted in Sweden ([Subramanian et al., 2016]) in a Norway Spruce (*Picea abies*) forest, we also found that lower intensities can contribute to total stand volume production. Our study shows that for thinnings from below, the most productive management is lowest intensity (i25) and lower frequency (f40) (Figure 5).

However, when analysing denser stands in Alberta, Canada, [Gupta et al., 2020] found that the total volume produced, considering intermediate volume production from thinning interventions, was higher in thinned scenarios than the control This result can also be seen in our study, since for stand D6, the denser stand, produced higher timber production in all the scenarios evaluated, while less dense stands were more susceptible to management changes in total timber production (Figure 5.

Another effect of commercial thinnings in the forest is the favouring of regeneration in the stand. The silviculture cost of planting new seedlings could be reduced in the next rotations if the population in the stand was already in development. We found that thinning intensity contributed significantly to regenerations, reaching its highest values for intensities i40.

The result described above corroborates the results found by [Olson et al., 2014], where the tree density ten years after the thinning was 10 times higher in thinned stands than in unthinned stands. This can easily be observed by the inverted J curve type in the tree density distribution in our study (Figure 8), found in the thinnings from below.

By analysing Figure 8 we can observe that the lowest diameter class (regeneration) did not account for any tree for frequency f35. What happened in this case is that the time of the last intervention in f35 until the final rotation age (120 years), did not allow the regeneration to reach maturity, and therefore the trees were considered saplings, and not adults.

Many authors found that thinnings can contribute to the increase in tree DBH, and therefore increase in individual tree volume. [Bose et al., 2018] registered an increment in tree volume growth of 31% in thinned stands when compared to unthinned stands, regardless of tree species and size, while [Gauthier et al., 2015] found increases of 12-18% in mean diameter for removals of 32-40% of basal area.

A study conducted by [Interior et al., 2006], found that the greatest response in individual tree growth can happen in the widest spacing, which could be converted in our case as the thinning intensity. Therefore, higher intensities and lower frequencies result in more trees in higher diameter classes, and consequently, higher DBH and volume per tree [Gauthier and Tremblay, 2019].

This can be observed in Figure 9, where the highest value for the highest diameter class can be found in high intensity (i40) and high frequency (f25). The effects of high-intensity thinnings in tree radial growth, with the addition of fertilization, were also registered in a study of Lodgepole Pine (*Pinus contorta*), conducted by ([Brockley, 2005]), where he identifies the shortening of rotation length as one of the benefits of accelerated stand development.

Thinnings from below, although resulting in lower stand volume production when compared to unthinned or thinning from above, have the benefits of increased regeneration and a significant increase in tree size. In this management, the low quantity of trees in high-diameter classes produces an important amount of volume at the end of the rotation. This volume has the benefit of being of much higher quality, and therefore, price.

With the increase in tree size, the wood originated from it can be used for a more "elegant" industry, such as flooring, furniture and construction for example. These products tend to carry a higher aggregative value, and therefore, could provide higher financial benefit for the forest owner.

4.3.2 Thinning from Above

The majority of the studies found considered thinnings as thinning from below, resulting in limiting information regarding thinnings from above. Our study shows a contrast in the results from these two different methods.

The first main difference is that, for all the stands analysed in this project, all the managements were positive when compared to the unthinned management (Figure 5), reaching their highest values for the densest stands (D6). However, this index symbolises the total stand production at the end of the rotation. When analysing the tree distribution in Figure 8, we can see that, contrary to thinning from below, there is no improvement in the average DBH of the trees, which happens due to the removal of the biggest trees in the previous interventions.

While thinning from below resulted in an inverted-J distribution curve, thinnings from above resulted in a much more similar to the normal distribution curve. This curve is very similar to the unthinned stand, with the difference of increased regeneration for high-intensity managements. Additionally, the volume in each of the diameter classes did not present significant changes from the unthinned management.

In any of the evaluated scenarios, and for all the stands analysed, thinnings from above resulted in higher timber production, enough basal area retention and volume harvested in each intervention. This means that, commercial thinnings are a practice that could contribute to increasing forest productivity for timber production. These managements could be utilized if the final goal of the forest is to promote total stand volume production, regardless of the size of the trees. Industries such as biomass for energy, pulp and paper and wood boards, where the wood would be chipped, could be benefited from this practice.

4.3.3 Continuous Cover Forestry - CCF

Continuous Cover Forestry (CCF) has been modelled through many different approaches, and the increase in computational power contributed to the evaluation of this management strategy. Although [Vanclay, 2012] mentions that stochasticity plays an important role in these simulations, due to the fact that regeneration and mortality are random, and also that the growth is calculated based on the effects of these two behaviours, for this study we found that the randomness did not influence the results.

However, this could be the result of a short (120 years) rotation cycle determined in this research. While the length used is enough to predict and simulate managements with a clear cut, this might not be the case for CCF. In the latter condition, it would be necessary to evaluate longer periods of time, since the benefits of CCF and the sustainability of a management regime might not always be accounted for in total in a time span of 120 years, but rather in longer rotation lengths ([Botkin, 1993] cited by [Vanclay, 2015].

Continuous cover forestry can improve the sustainability of forest management, especially when considering ecosystem services [Kiisel and Remm, 2022]. The initial idea of this study was to include the valuation of ecosystem services for the different management alternatives. This would give us a more complete basis for decision-making and the sustainability of forest management. It was already expected that timber production would be much lower than clear cut managements, however, in the selection of the best management regime it is important to evaluate not only timber production, but also its implications for natural habitats, biodiversity, social and cultural aspects of forests ([Tahvonen and Rämö, 2016], [Köhl and Baldauf, 2012] and [Pukkala et al., 2012]).

The changes in forest management from a clear-cut point of view to the CCF, have been applied on different continents. In Europe, there is a willingness for this transformation because this management has the potential of increasing biodiversity and promoting more resilient forests to the effects of climate change [Vitkova and Dhubháin, 2013]. This approach is of extreme importance for countries that are susceptible to extreme events, such as Canada.

This study showed that timber production is significantly lower for CCF when compared to clear-cut, but also the retention of trees in the stands is in accordance with the removal rates. The edges of each of the graphs in Figure 6 show that extreme lower and higher frequent and intense interventions result in either over or under-accepted tree retention for a CCF strategy.

By only analysing timber production, and recognizing its limitations, the best alternatives found were the intermediate frequencies and intensities, where we can find a balance in intensities i30 and i40 and frequencies of f30 and f35.

4.4 Commercial Thinnings in British Columbia

In British Columbia, almost the entire forest land is owned by the Crown, and therefore many different tenure licenses were created to manage and control timber production. A key concept for understanding this regulation is to differentiate volume-based tenures and area-based tenures. The first one grants the right of harvesting a specific amount of timber from the Timber Supply Area (TSA), while the second grants exclusive harvesting rights for a specific area [MFLNRORD, 2012b].

According to BC's government, in 2012, nearly 80% of the forest resources were under volume-based tenures, and only 20% under area-based tenures such as Tree Farms Licenses (TFL), and other agreements [MFLNRORD, 2012a]. In 2018, the proportion of volume-based licenses increased to 90%, and still considered management until the "free-to-grow" state of the forest. Free-to-grow strategy only accounts for 10 to 20 years of forest regeneration and reforestation, where the forest cycle can be eight to ten times longer than that [Devisscher et al., 2021].

Some authors ([MFLNRORD, 2012a]) identify the disadvantages of area-based tenures as: negative public perception; first-nations conflicts due to land disputes; competition to other types of area-based programs (community forests and First nations licenses, for example); and loss of government flexibility to forest management.

However, the consequence is the transfer of the liability of silvicultural operations from the licensee to the government, and the monitoring and managing of the stand conditions would not support the long-term objectives of silvicultural interventions [Mitchell et al., 2017], such as commercial thinnings. The author also suggests that the current free-to-grow policies do not contribute to developing yield and growth projections and that after the responsibility is transferred back to the government, there is no intermediate monitoring and actions to guarantee future results from the forests.

In 1988 there was an attempt from the government to modify some volume-based tenures into area-based. However, at the time, the public demonstrated some resistance to this legislation due to the worry of privatization of land and a lack of forest management [Collective, 2014]. A more recent survey, conducted in 2019, with more than a thousand people involved in the forestry sector in BC shows some feedback and perspectives regarding the sector [Ministry of Forests, 2020]. According to the results, 41% of the participants identify "Forest tenure and fibre supply" as one of the areas of most important policy areas.

Among one of the suggestions from the interviewers to the government is to "prioritize area-based tenures". Despite not being as common as volume-based tenures, many benefits can come from this approach, such as: ecosystem protection and forest sustainability;

long-term investments incentives and partnerships ([Ministry of Forests, 2020]); recreational value; stable future wood supply ([Frazer, 2022]); increasing forest management practices ([MFLNRORD, 2012a]).

Improving forest management practices, such as fertilization, selection and planting of improved seedlings, as well as the application of commercial thinnings can contribute to improving forest productivity and work as a tool to reduce the forest rotation cycle. The results of this study shows that commercial thinnings can guide and change the future of our forests based on our goals. Therefore, by incentivising area-based tenures, and consequently increasing forest management practices in British Columbia, we could contribute to more resilient and value-oriented forest practices, and as a result a more effective forestry sector.

5 Conclusion and Further Research

5.1 Conclusion

This study focused on evaluating different thinning regimes in interior British Columbia to better comprehend the impacts and influences of each of the variables in timber production at the end of a forest rotation cycle. We found that skidding track distances do not significantly affect timber production and that stochasticity did not influence the SORTIE-ND simulations. We also found that all the managements from above complied with the Commercial Thinnings Guidelines of British Columbia, and that high intensities and high frequencies regimes from below violated the basal area retention requirements of the guidelines. Also, in every scenario from below the managements did not fulfill the minimum harvested volume in each intervention (50 m^3/ha).

The results show that total timber production at the end of the cycle was favoured by high intensity and frequency for managements from above, and low intensity and low frequency benefited timber production for managements from below. Continuous cover forestry produced significantly less timber at the end of 120 year-cycle, while middle frequencies and intensities managements contributed to a balanced removal rate and volume retention in the stand.

We also found that regeneration is favoured by increasing light and space, resulting from heavier thinning managements, having significant differences between above and below. The latter presented much higher values for regeneration. Additionally, this management resulted in improved stand structure, by increasing the diameter class distribution, especially a significant increase in abundance of trees in diameter classes above 35 cm, resulting in important high-quality volume for these regimes.

Different managements can be used for different purposes. The goal of this study was to understand the consequences of different management regimes in timber production. We also found that, if the goal of the manager is to increase stand volume, thinnings from above could be the best alternative, since in all the situations thinning regimes produced more timber than the unthinned regime at the end of the 120 cycle. In contrast, thinnigs from below, although not always resulting in higher timber production than the unthinned management, resulted in a significant increase in the DBH of the remaining trees, therefore producing higher quality wood that could be destined for more high-quality demanding industries.

5.2 Further Research

This study, as any other, has its limitations, and therefore more research could and should be conducted to better understand the additional effects of thinning regimes on forest characteristics, timber production and ecosystem services provided by vegetation. below we list some of the possibilities for further assessment of CTs that could contribute to decision-making:

- Additional ecosystem services should be evaluated to provide more substantial comparison indexes of each of the managements regimes, specially when considering CCF strategy.
- Include an economic evaluation that estimates the most profitable management regime, including operational costs and merchantable timber prices;
- The CCF regimes should be processed in longer simulation lengths to better understand the sustainability of this management and assess the stochasticity;
- Apply the same approach in stands with a wider range of initial characteristics such as tree composition, basal area and tree densities;
- Analyse composition effects of the managements (species) to understand if there is any difference in the species mix at the end of the rotation.

Supplementary Material
Appendix A, B, C

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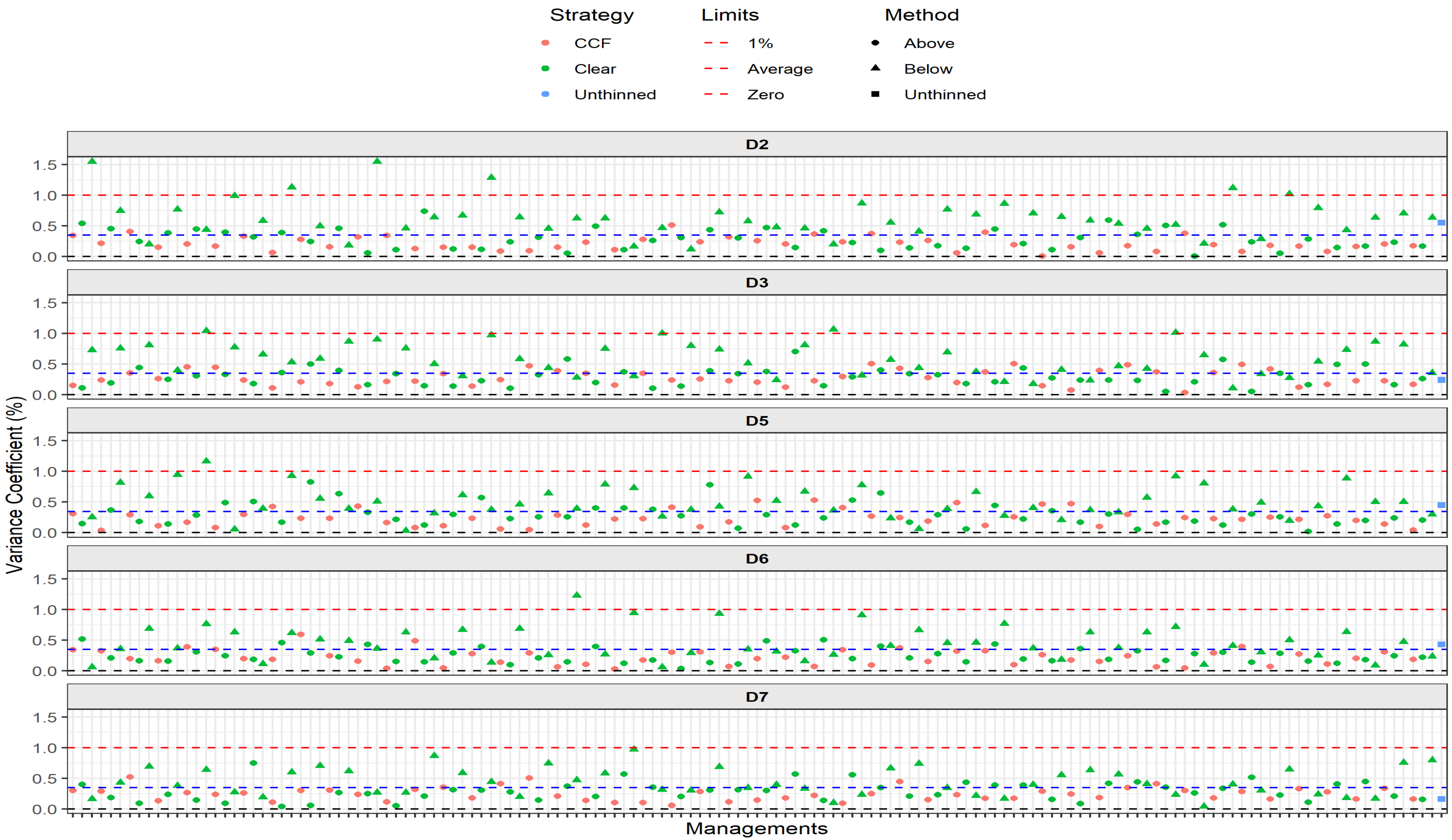
Appendix A - Mean Variance for the Repetitions

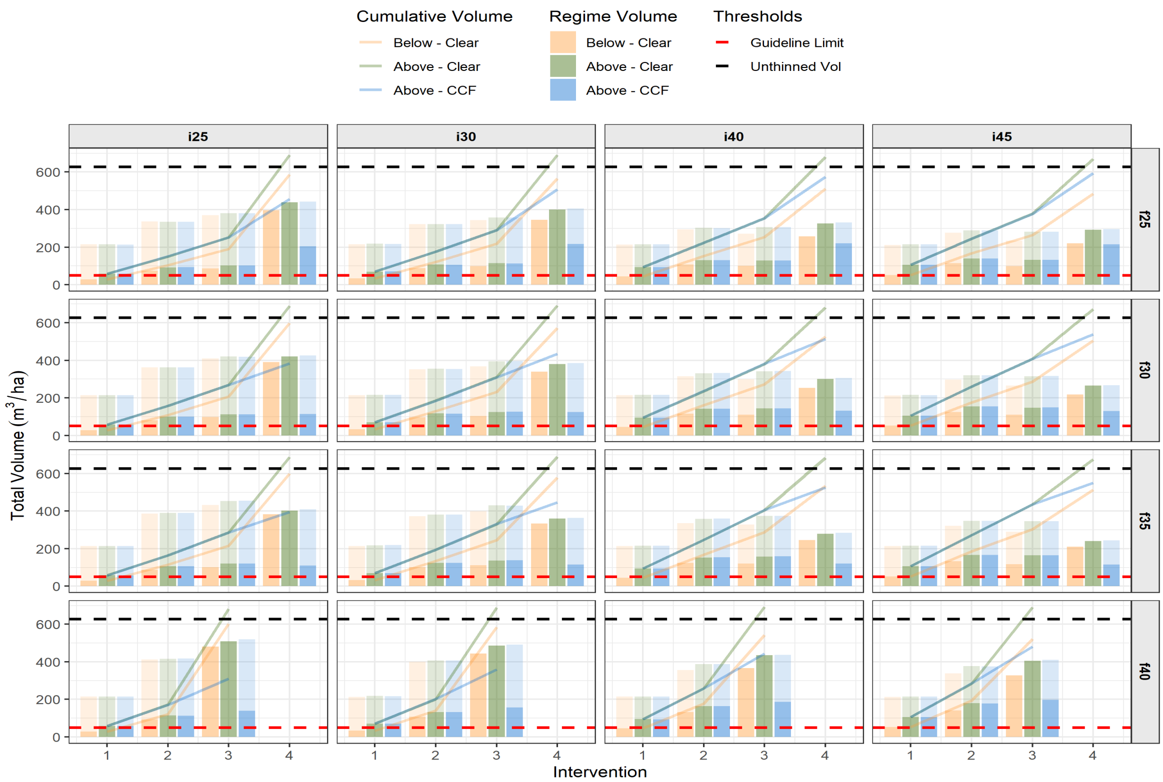


Appendix B - Volume Harvested per Time Step

Stand D2

Stand D3

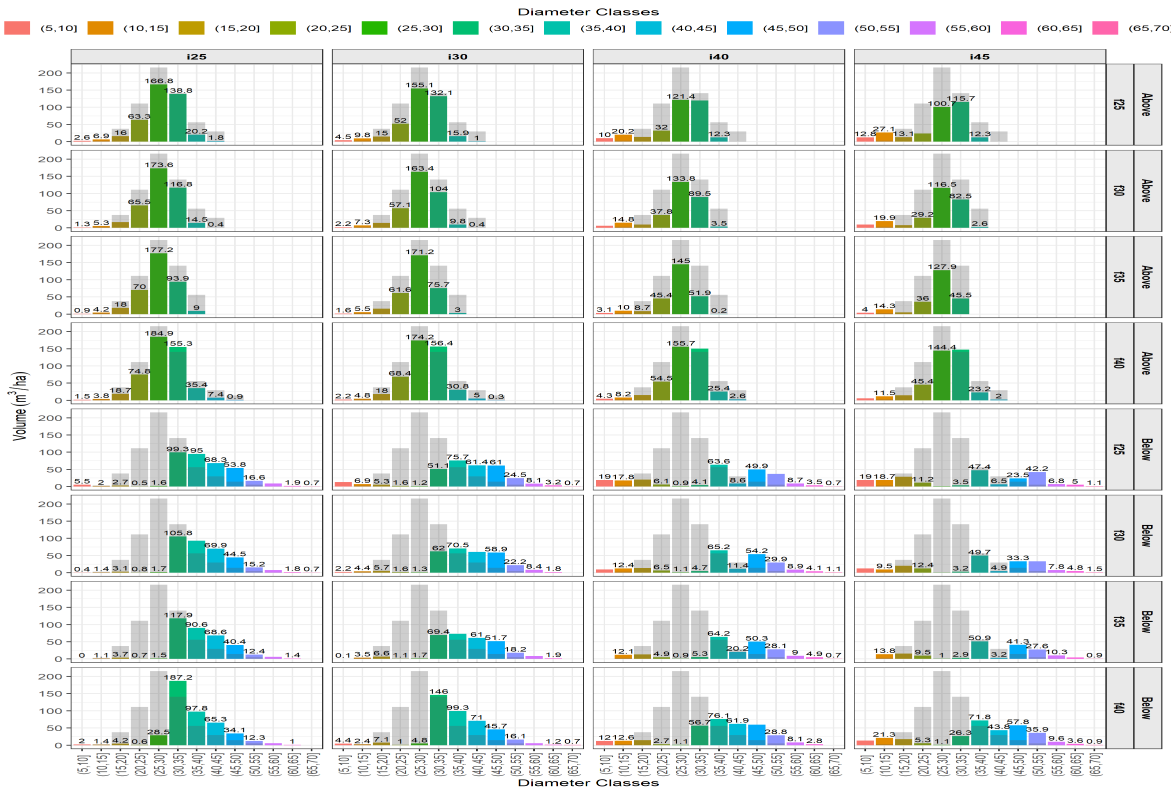
Stand D5



Stand D7

Appendix C - Density and Volume per Diameter Class

Stand D2



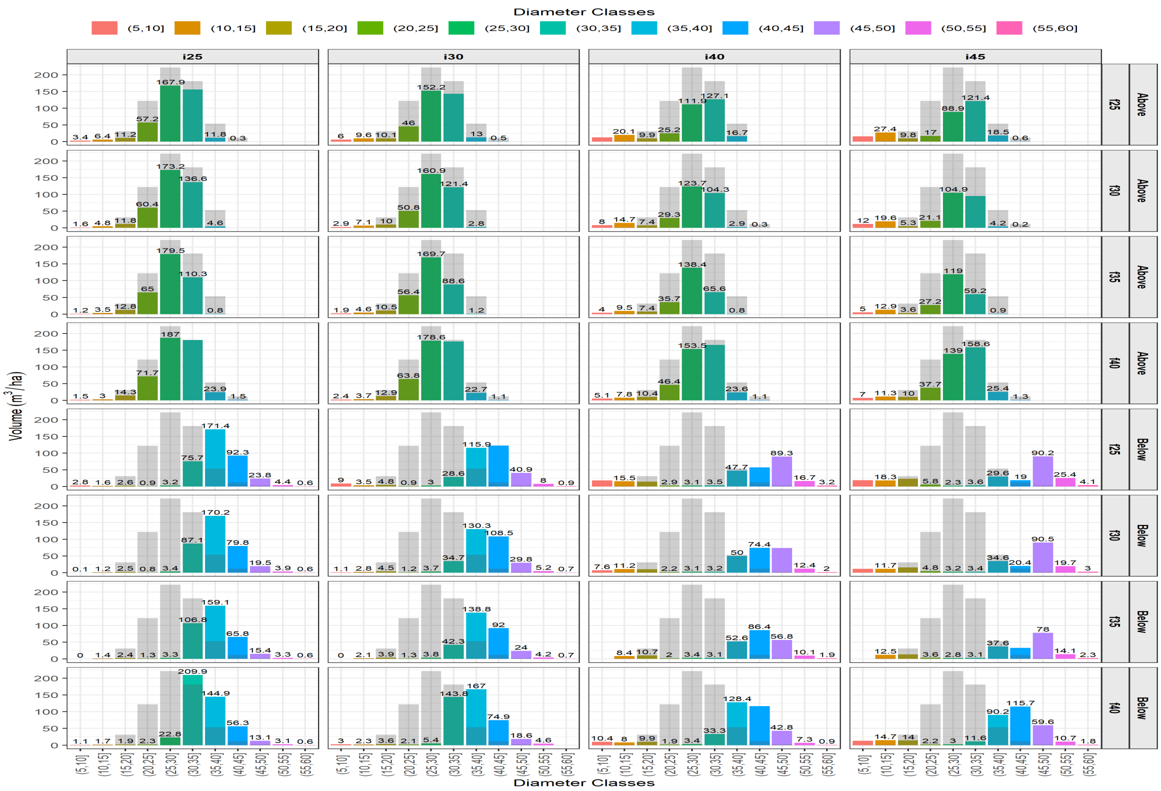
Stand D3


Diagram Classes
(5,10] (10,15] (15,20] (20,25] (25,30] (30,35] (35,40] (40,45] (45,50] (50,55] (55,60] (60,65] (65,70]
i25
i30
i40
i45
t25
t30
t35
t40
Above
Below
Density (trees/ha)
600
400
200
0
Diameter Classes


Diameter Classes
(5,10] (10,15] (15,20] (20,25] (25,30] (30,35] (35,40] (40,45] (45,50] (50,55] (55,60] (60,65] (65,70]
i25
i30
i40
i45
t25
t30
t35
t40
Above
Below
Volume (m³/ha)
250
200
150
100
50
0
Diameter Classes

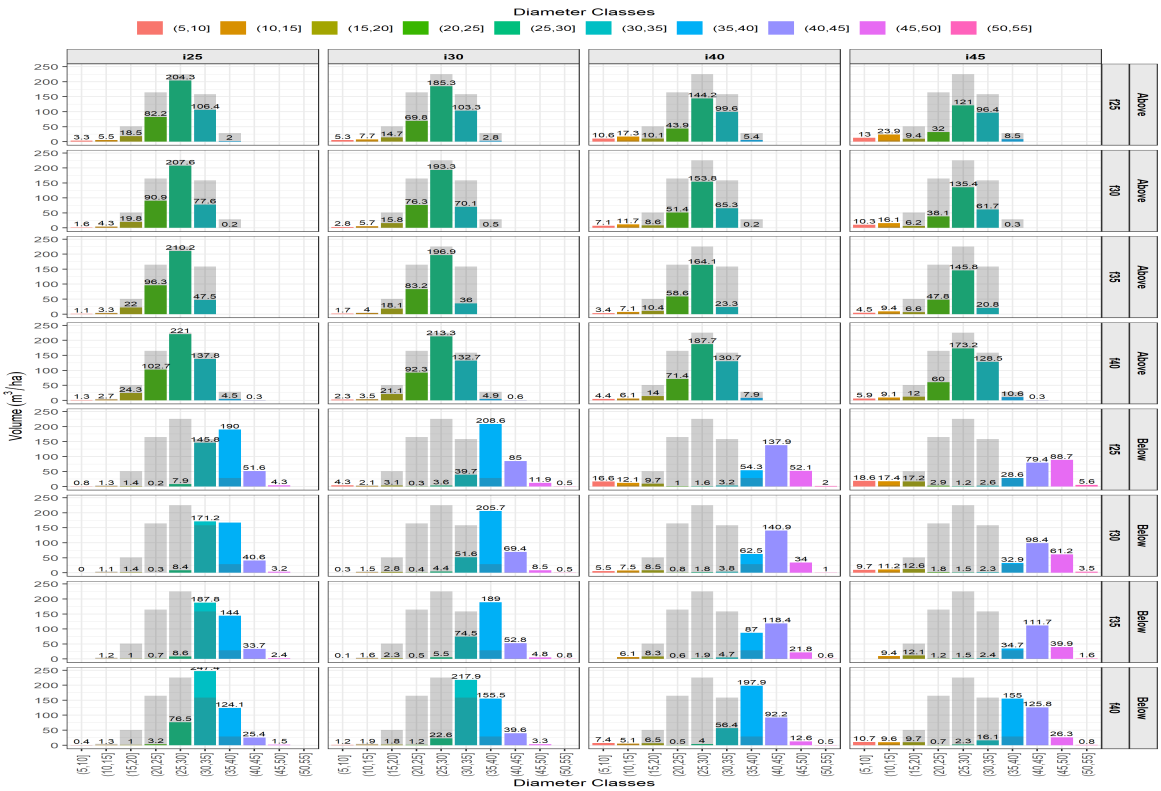
Stand D5


Diameter Classes
(5,10]
(10,15]
(15,20]
(20,25]
(25,30]
(30,35]
(35,40]
(40,45]
(45,50]
(50,55]
(55,60]
i25
i30
i40
i45
Density (trees/ha)
Above
Below
Diameter Classes


Diameter Classes
(5,10]
(10,15]
(15,20]
(20,25]
(25,30]
(30,35]
(35,40]
(40,45]
(45,50]
(50,55]
(55,60]
i25
i30
i40
i45
Volume (m³/ha)
Above
Below
Diameter Classes

Stand D7

Diameter Classes
(5,10] (10,15] (15,20] (20,25] (25,30] (30,35] (35,40] (40,45] (45,50] (50,55]
i25 i30 i40 i45
Above
Below
Density (trees/ha)
Diameter Classes



Diameter Classes
(5,10] (10,15] (15,20] (20,25] (25,30] (30,35] (35,40] (40,45] (45,50] (50,55]
i25 i30 i40 i45
Above
Below
Volume (m3/ha)
Diameter Classes