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Abstract

Thinning is the partial removal of trees in a forest stand prior to final harvest. The term can be divided in pre-commercial thinning where little if any volume is removed from the stand and commercial thinning where removals are intended to provide a positive economic result. From a silvicultural point of view, the goal of thinning is to enhance future crop tree quality by removing low-quality stems and providing sufficient space for the accelerated development of retained ones (Huuskonen & Hynynen, 2006).

The goals of this study was to see if commercial thinning could positively affect the short and medium term timber supply (MTTS) in the Interior regions of British Columbia (BC), and whether or not Scandinavian forestry practices could be adopted in the BC context. The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) has created significant forest planning problems in BC. The annual allowable cut (AAC) was raised to capture beetle-killed timber while still merchantable. These regions face drastic cuts in AAC in the mid-term, and the provincial authority is looking to mitigate the effects of this falldown, and commercial thinning has been suggested. The effects of commercial thinning on the provincial timber supply was analysed in three ways: a literature review, a series of stakeholder interviews, and a case study for the Alex Fraser Research Forest.

A review of thinning regimes in Nordic countries shows thinning has beneficial consequences on timber quality, with small decreases in total volume. Merchantable volumes are similar to unthinned stands, ranging from a decrease (ca. 20%) in Scots pine (*Pinus sylvestris* L.) to a slight increase (0-5%) in Norway spruce (*Picea abies* L.). Average tree diameters are greater in thinned stands, a determining factor in stand culmination. Thinning provides intermediate sources of timber and income before final harvest.

A series of interviews with important stakeholders in the Swedish forest sectors shows that commercial thinning plays an important role for the timber supply and the economy of their industries. All report that thinning is ubiquitous in “proper forest management”. On an area basis, two thirds of the yearly harvest is the result of thinning, producing one third of total volume. In comparison, final harvests are conducted over the remaining one third of the harvested landbase and account for two thirds of the timber supply. The thinning programmes in place are a result of the young age-class structure of the forest.

The case study was conducted at The University of British Columbia’s Alex Fraser Research Forest (Beaver Valley, BC). A 2200 ha subset of the Gavin Lake block of was classified by maturity level, with a particular interest for stands suitable for a first thinning. A total of 957 ha have thinning opportunities, with an average of 120 m^3/ha available for harvest during at first entry; a total of 102 458 m^3 would be made available with thinnings. Partial harvests of these stands could improve the short-term and mid-term timber supply while providing beneficial effects (quality, age-class distribution) in the mid and long-term.

Commercial thinning could play a part in filling a MTTS gap, by providing timber before final harvest, by controlling timber flows from thinned stands, by creating more merchantable sawlog volume, by accessing timber in visually sensitive areas, and by using the shelterwood regeneration method in hard to regenerate areas. Certain practices from Nordic countries are currently adaptable to the BC context, while others would require longer-term changes for the industry.

Keywords: forestry, silviculture, commercial thinning, mid-term timber supply

Sammanfattning

Gallring är en beståndsvårdande åtgärd som syftar till att öka ett bestånds framtida virkeskvalitet samt ge ett positivt ekonomisks resultat. Genom att avverka stammar av låg kvalitet påskyndas utvecklingen av de kvarvarande stammarna (Huuskonen & Hynynen, 2006).

Studiens syfte var att undersöka om gallring kan ha en positiv effekt på virkesförsörjningen både på kort och på medellång sikt i British Columbias inre regioner samt huruvida skandinaviska skötselmetoder kan appliceras i British Columbia. Contortabastborrens (*Dendroctonus ponderosae* Hopkins) framfart har lett till stora planeringsproblem för British Columbias skogssektor. Nivån på den tillåtna årliga avverkningen har ökat för att kunna rädda stora volymer av det skadade timret, men på medellång sikt kommer dessa regioner uppleva en drastisk reduktion i den tillåtna avverkningen. Provinsens myndigheter försöker mildra effekterna av denna minskning och implementering av gallring är ett av förslagen. Effekten av gallring på den provinsiella virkesförsörjningen analyserades genom en litteraturstudie, intressentintervjuer och en fallstudie i Alex Fraser Research Forest.

Litteraturstudien visade att gallring i Norden påverkar virkeskvaliteten positivt men medför en minskning i beståndsvolym. Slutavverkningsvolymen av kommersiellt gångbart timmer i gallrade bestånd visar allt från en minskning av ca 20 % i tallskog (*Pinus sylvestris* L.) till en mindre ökning (0-5 %) i granskog (*Picea abies* L.) jämfört med ogallrade bestånd. Medelstammen är grövre i gallrade bestånd, en betydande faktor för rotationsperiodens längd. Gallring bidrar även med virke och inkomst under omloppstiden.

Intervjuer med intressenter inom den svenska skogsindustrin visar att gallring är viktigt för virkesförsörjningen och industrins ekonomi. Gallringar står för två tredjedelar av den årliga avverkade arealen och producerar en tredjedel av den avverkade volymen. Den gallringsregim som följs är ett resultat av skogarnas ålderklassfördelning.

I fallstudien i Alex Fraser Research Forest ingick 2200 ha skogsmak som klassificerades med avsikt på ålder och med fokus på att hitta gallringsskogar. Gallringspotential hittades på 957 ha där 120 m^3/ha och totalt 102 458 m^3 var tillgängligt för avverkning vid första gallring. På kort och medellång sikt skulle gallringar i dessa bestånd kunna leda till ökade avverkningsvolymer och samtidigt ha goda konsekvenser på lång sikt med avseende på virkeskvalitet och åldersklassfördelning.

På medellång sikt skulle gallring kunna hjälpa till att fylla virkessvackan genom att producera timmer under tillväxtiden, kontrollera timmerflödet från gallrade bestånd, skapa större virkesvolymer, avverka i visuellt känsliga områden och skapa skärmträd i återväxtkänsliga områden. Några skötselmetoder från de nordiska länderna skulle redan idag kunna användas i British Columbia, medans andra kräver långsiktiga förändringar inom skogsindustrin.

Nyckelord: skogsbruk, skogsskötsel, gallring, virkesförsörjning

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List of terms and abbreviations

AAC	Annual allowable cut: The rate at which timber may be harvested in any given Timber Supply Area as determined by the chief forester, taking into account social, economic and environmental considerations
AFRF	Alex Fraser Research Forest: The University of British Columbia's Interior research forest, and the location of the case study.
BA	Basal area, expressed in m^2/ha. The area of the cross-section of trees measured at breast height in a hectare.
BC	The province of British Columbia, Canada
BEC Zone	Biogeoclimatic zone of British Columbia: A classification system based on ecosystem (Bio) –geography (Geo) –climate (Climatic) to guide management practices.
Cubic meter	Given in m^3sk, or "standing volume in the forest", measured as total stem volume from stump to top including bark.
DBH	Diameter at "breast height", measured 1,3 m above the ground, perpendicular to the stem.
MTTS	Mid-term timber supply: The timber supply available in approximately the next 20 – 60 years. Most trees contributing to the MTTS are already growing today. New plantations will contribute to the long-term timber supply (60+ years), while harvest blocks ready for harvesting contribute to the short-term timber supply (0-20 years).
The Interior	One of the three regions which the province of British Columbia is typically divided into (the other two being the Lower Mainland and the Coast. The Central and Northern Interior regions are host to much of the mountain pine beetle infestation.
LTSY	Long-term sustainable yield: The product of the area of the timber harvesting landbase times its the maximum growth rate.
PCT	Pre-commercial thinning is the early harvest of stems for the benefit of the remaining stand. Trees are typically left in the forest to decompose.
Thinning	Thinning is the removal of merchantable-sized timber before the final harvest, for the benefit of the remaining stand.
THLB	Timber harvesting landbase. The area capable of supporting forestry activities based on social or operational constraints.
Timber supply	The availability of timber over time; the potential flow of logs from the forest (Pedersen, 2003).

TSA Timber Supply Area: An area designated by the Ministry of Forests, Lands and Resource Operations where integrated resource management takes place. The unit as the basis for local AAC determinations.

TU Treatment unit: A unique name given to each of the management units used in the classification of the Gavin Lake block of the Alex Fraser Research Forest for this study.

Site index (Sweden/Finland)

- Eg: T25. Scots pine (Swedish *Tall*) with a predicted dominant height (25m) at *100 years* of age.
- Eg: G25. Norway spruce (Swedish *Gran*) with a predicted dominant height (25m) at *100 years* of age.

Site index (BC)

- Eg. H25. The "leading species" with a predicted dominant height (25m) at *50 years* of age. Most sites are mixed-species sites, and no prefix is used to describe the leading species.

1 Introduction

Thinning is the partial removal of stems prior to the final harvest of a forest stand. The goal of thinning is to enhance future crop tree quality by shifting the available resources (eg. Water, nutrients, light, space) to selected stems, while accelerating individual tree growth, especially diameter development (Huuskonen & Hynynen, 2006; Mäkinen & Isomäki, 2004a).

The term “thinning” can be divided into pre-commercial thinning (PCT) and commercial thinning (or simply thinning). In PCT, the early harvest of stems for the benefit of the remaining stand will likely incur a cost to the forest owner; removals are typically left in the forest to decompose. In contrast, commercial thinning is the removal of “merchantable-sized” timber for the benefit of the remaining stand, and is expected to generate a positive economy or at the least to finance itself. However, the boundary between the terms is constantly evolving. For example, with the increased demand for biofuels in Finland and Sweden, what is considered a *pre-commercial* thinning can still generate some income. In this paper I refer to thinning as the removal of merchantable-sized timber (pulp and sawlogs) capable of contributing to the timber supply, specifically referring to conifer forest types.

1.1 The mountain pine beetle epidemic in central British Columbia, Canada

The BC Ministry of Forest, Lands and Natural Resources Operations recognises the challenges the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (MPB) epidemic poses to the mid-term timber supply (MTTS) and the communities that rely on it:

> *The current mountain pine beetle epidemic in Interior British Columbia will result in a drastic decrease in timber supply in some areas, with potential for significant negative economic and social effects to the forest industry and forestry-dependent communities.*
>
> (Ministry of Forest Lands and Natural Resources Operations, 2012).

The Interior of BC has been affected by the largest mountain pine beetle epidemic on record, affecting approximately 17,5 million hectares and killing 730 million cubic metres – approximately 10 years of the provincial annual allowable cut (AAC). The AAC is determined for various timber supply areas (TSAs) using a variety of tools and information. It is based on the long-term sustainable yield (LTSY) but also incorporates societal (eg. visual quality) and environmental values (eg. wildlife and watershed management). The AAC can be raised to above-LTSY levels to respond to natural disturbances. To capture the beetle-killed timber before it became unmerchantable, the AAC was increased in various TSAs in the Central Interior. Following the uplift, a downfall in the AAC will ensue, and a gap in the MTTS starting in ca. 5-10 years and lasting approximately 50-70 years. The MTTS is described as “the period between the ending of the economic shelf-life of killed pine and the time when the forest has regrown and become merchantable again” (The Minister of Forests, Pat Bell 2010). The Lakes, Quesnel, Prince George and Williams Lake TSAs are the most affected by the MPB epidemic, and all face significant decreases in AAC, starting in 2015-20 and lasting till 2060-70.

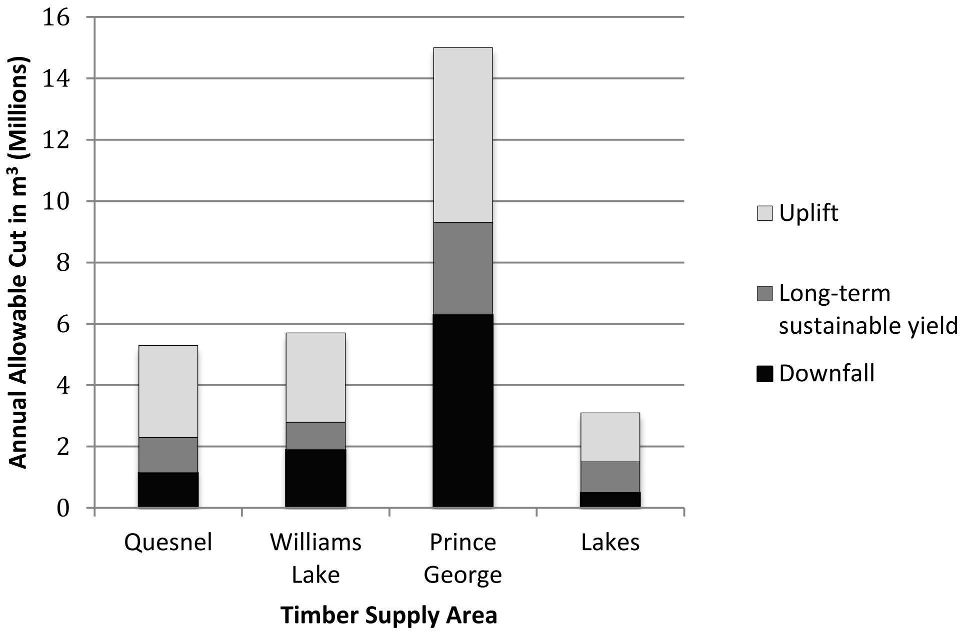


Figure 1 - Annual allowable cut uplifts and downfalls in four Central Interior (BC) timber supply areas as a result of the mountain pine beetle infestations (Ministry of Forest Lands and Natural Resources Operations, 2012)**.**

In early 2012 the BC government assembled the Special Committee on Timber Supply to look at different ways to mitigate the effects of the AAC downfall to the MTTS. Among others, commercial thinning was recommended as one of the silvicultural measures capable of helping with the MTTS. Commercial thinning affects the timber supply in a number of ways:

- Thinning in immature stands provides some timber in the short term while increasing quality and accelerating the time to culmination (based on diameter development) of retained stands.
- Thinning in middle-aged stands not quite ready for final harvest provides a good amount of timber, with some quality and diameter increment gains expected at final harvest.
- Thinning in appropriate mature stands provides the most timber in the short term while extending the rotation of the stand to culminate in the mid-term. This can be used to manage timber flows.
- Thinning captures some of the natural mortality otherwise be lost to decay.
- Thinning could be conducted in visually sensitive areas currently excluded from the timber harvesting landbase
- Thinning reduces the waste volume at the time of final harvest.

Moreover, thinning affects the economy of a stand in a number of ways:

- Income is generated at the first thinning, while retained individual stems grow larger, this
- Reduces future per-cubic-meter harvest costs and
- Increases the value of each cubic meter.
- Thinning allows for species selection, shifting growth to the most valuable species.
- Thinning contributes to healthy stands, making them more resistant to biotic and abiotic factors.
- By focusing the diameter growth on quality stems, rotations can be shortened.

However, thinning in BC is not a common practice. Only approximately 0,1% of the forest landbase is thinned, and this is mostly in coastal regions with very different climatic and growth conditions than the Interior of BC. Therefore, it is useful to look abroad to jurisdictions with similar enough forest types with more experience in thinning to develop adequate thinning programmes for the Interior. My studies in Sweden lend well to examining forestry practices from Nordic countries such as Sweden and Finland, where thinning is common and good information is readily available.

The case study for this thesis was conducted for the Alex Fraser Research Forest (AFRF) whose purpose it is to provide education, research and demonstration opportunities for all aspects of forest management, including "the impact of intensive forestry treatments on forest growth" (Klinka et al., 2004). The potential for developing BC-specific thinning practices, conducting trials and eventually, outreach to industry was one of the goals for the case study and is concordant with the mandate of the AFRF as a research institution and the government's goals of mitigating MTTS gap effects.

1.2 The history of thinning in Finland and Sweden

Thinning has for a long time been a recommended practice in Finland and Sweden. In Finland, the first growth and yield data for thinning in Norway spruce was published in 1878 (Blomqvist 1878, in Mäkinen & Isomäki, 2004). In Sweden, thinning was already a recommended from the mid-19th century onwards (Wallentin, 2007).

Early thinning practices, developed during the 19th century, date back long before becoming commonly accepted. 100 years ago, sawmilling was the major industry in Sweden, while pulp and paper played only a small role. As the pulp industry grew, it required more and more fibre. To expand pulp production, thinning became more and more popular. The expansion of the pulp industry did not take away from sawmilling; in fact it improved timber quality for sawmilling industries. The pulp industry, using volumes from thinning, was a way to increase production using the same fixed landbase. Thinning, on a commercial scale, was a direct response to the pulp industry's need for fibre, being the only new fibre supply available.

Until the mechanisation of forestry activities in the 1950's and 1960's, thinning was mostly limited to frequent, light removals of small-diameter, dead, dying or suppressed trees (Wallentin, 2007). Mechanised thinning has brought about a change in thinning practices, from frequent to fewer treatments and from light to heavy removals, and an increase in time between entries (Nilsson et al., 2010). Over 90% of thinnings are now mechanised in Finland (Kärhä, Rönkkö, & Gumse, 2004), starting in the early 1960s mainly due to the mechanisation of harvesting operations (Mäkinen & Isomäki, 2004b). Mechanised thinning increased from about 0% to 60% between 1970 and 1990 in Sweden (Axelsson, 1998), and have since progressed following the Finnish trend. The current figures for Finland and Sweden are likely around 95% mechanised thinning – the exception being small-scale landholdings (Anders Karlsson 2012, pers. comm.). However, at the start of mechanised falling in the early 1970's, productivity in thinnings was low, and thinning was considered too expensive to justify. Newly established stands were widely spaced and heavily pre-commercially thinned; envisioning an entire rotation without thinnings. With dramatic increases in productivity and good timber prices, these very stands are now being thinned throughout Sweden and Finland.

There are a few descriptors used when discussing thinning. *Thinning intensity* relates to the amount of trees to be harvested, typically expressed as a percentage of the basal area or a percentage of stems compared to the site before the treatment. *Timing and frequency* relate to the number of thinning treatments and the age or other measure of stand development (eg. Top height, crown closure, etc.) at which the treatment takes place. *Spatial distribution* relates to the stand structure and species selection of the residual stand. *Thinning type* relates to the tree class selected for during thinning (Wallentin, 2007). A commonly used measure of thinning type is the *thinning ratio*, expressed as d/D where d is the mean DBH of trees harvested and D is the mean DBH of the stand before thinning. Thinning from below removes the small-diameter, low vigour or dead and dying trees in the intermediate and suppressed crown classes and concentrates growth on dominant trees (Jessie, Graham, & Harvey, 1999). Thinning from above removes trees from the dominant crown class, leaving room for smaller developing trees (Nilsson et al., 2010). Crown thinning is a type of selective thinning where the best stems are selected, and the thinning regime aims to give these trees the available space for rapid crown development (the photosynthetic driver of tree growth); cuttings are not limited by crown class (Wallentin, 2007).

1.3 Current thinning practices in Finland and Sweden

The essential practices are cleaning, PCT, thinning (from 1 to 3), final harvest, followed by new stand establishment (scarification followed by planting/sewing/natural regeneration). Between 2000 and 2500 stems per hectare are planted, supplemented by natural regeneration. Cleaning and PCT typically starts at 1,5-2 m height (cleaning), and is repeated at a height of 4-5m (PCT). High fertility sites may require a second PCT, which may be avoided with a delayed first PCT. Care is taken to release planted stems to make use of enhanced genetics. Natural regeneration and broadleaves are retained when and where planted crop trees do not survive. Approximately the same number of planted stems are expected to survive to the first thinning. Cleaning and PCT generally eliminate “surplus” stems, ie. natural regeneration and non-preferred species.

The first commercial thinning removes 35%-40% basal area (BA) (including strip roads) when trees reach 12-14m heights. The second thinning removes 25-30% of the BA when trees reach ca. 17-19 m. Both thinnings are from below, with a thinning ratio of ca. 0,80 for the first thinning, and 0,85 during the second thinning. Establishing strip roads as well as harvesting dead, dying, low-vigour and damaged trees contribute to the higher BA removal of the first thinning. Economic rotations based on net present value calculations are as low as 60 years for spruce growing on the most fertile sites. Lower site fertility have rotations up to 100 years. The interest rate is that used by the Swedish Forest Agency.

Table 1 - SveaSkog's thinning regime for Scots pine and Norway spruce growing for different site qualities. Economic rotation calculated using 2,53% interest rates (Sonesson & Rosvall, 2011)**.**

Species	Site index	No. of stems planted	No. of stems after cleaning	No. of stems before 1st thinning	1st Thinning			Second thinning			Economic rotation (years)
					Top height (m)	BA removal %	Thinning ratio	Top height (m)	BA removal %	Thinning ratio	
Pine	T18	2000	1600	1400	12	40	0.87				94
	T22	2200	1900	1700	13	35	0.82	17	0.25	0.82	81
	T25	2400	2000	1850	13	35	0.82	18	0.3	0.88	71
	T28	2600	2200	2000	13	35	0.82	18	0.3	0.87	61
Spruce	G20	1700	1500	1400	14	35	0.82				100
	G26	2200	2000	1900	14	35	0.82	19	0.3	0.89	83
	G32	2300	2100	2000	14	35	0.82	19	0.3	0.81	60

1.3.1 The importance of pre-commercial thinning

PCT is an expensive investment in stand management due to high labour costs and little to no income to offset this. However, it is considered an investment required in forest management, both for tree growth and stand operability. Despite efforts to mechanise PCT (Nordfjell, Ligné, & Karlsson, 2005), practical solutions do not exist yet and the motor-manual method using a brush saw remains the only option in common practice. PCT has a significant effect on the diameter development of the remaining trees (Huuskonen & Hynynen, 2006). PCT also affects the stand's operability for the harvester during the first thinning. Tree size and machine productivity both positively affect the economy of the first thinning and will determine whether the thinning will be profitable or not. Thus, even though mandatory PCT was removed from Swedish legislation in 1993 (PCT in Finland, while not mandatory, is still subsidised by the State), forest owners realise they must do a PCT sooner or later. Delaying or omitting the PCT has negative effects on growth and stand management. Diameter growth of remaining trees is stunted, reducing volumes and profitability of first thinnings and the first thinning must be delayed to account for slower diameter growth.

Wide initial spacing could reduce the dependence on PCT to achieve desirable stocking levels. However, wood quality is jeopardized by creating stems with longer, thicker branches at high branch angles (Magnussen & Yeatman, 1987). Furthermore, planting densities are often supplemented by natural regeneration, meaning regeneration stocking is above planting levels. Just as wide initial spacing has negative impacts on wood quality, dense spacing and a later PCT can have beneficial effects on stems grown for high quality sawtimber, with decreased branch size and a longer clear bole (Ruha & Varmola, 1997). The compromise in PCT intensity will be to balance removing too many stems, affecting future yield losses, and removing too few, affecting timber quality. PCT has other impacts on the stand:

- Regulation of stand density affecting quality development
- Selection for quality where stems with obvious damage are removed
- Creation of a stand with even tree spacing and distribution
- Removing competing trees of undesirable species
- Increasing diameter development enabling a timely first commercial thinning
- Enabling a mechanised first thinning

1.4 Goal of the current study

The aim of this present study is to evaluate potential commercial thinning opportunities in the Interior of BC, and their ability to significantly contribute to the timber supply gap in the mid-term. The effects of Swedish and Finnish thinning practices on tree and stand growth will be reviewed from literature, and assessed for their contribution to the MTTS. The importance of thinnings to the timber supply and its prevalence in forest management in Sweden and Finland was explored with interviews conducted with stakeholders in Swedish forestry. Finally, a case study was conducted in the Gavin Lake block of the AFRF, evaluating current thinning opportunities. The forest condition of the area selected for the case study makes it possible to extend some of the findings to other regions of the Interior.

2 Materials and methods

2.1 Literature Review

The literature review focused on three aspects of thinning. The first topic explored was tree (quality and diameter) and stand (growth and yield) responses of Scots pine and Norway spruce to various thinning frequencies and intensities in Sweden and Finland. The studies reviewed in this paper summarise long-term thinning experiments on permanent sample. Plots for the Swedish study were established between 1966 – 1983 (35 plots for pine and 13 plots for spruce) with an average measurement period of 30 years (pine) and 31 years (spruce) (Nilsson et al., 2010). Plots for the Finnish studies were established during the 1960's and 1970s (37 plots for pine and 21 plots for spruce) with an average measurement period of 25 years (pine) and 28 years (spruce) (Mäkinen & Isomäki, 2004a, 2004c). The studies all compared thinning treatments from light to heavy BA removal, as well as thinning from above and below, to control plots.

The second topic explored were some of the risks associated with thinning. Windthrow risk is increased immediately following thinning. Long-term data for permanent plots was not available but reports following major storms in Finland and Sweden were reviewed (Pellikka & Järvenpää, 2003; Valinger & Fridman, 2011; Valinger & Pettersson, 1996). Stand characteristics and their susceptibility to storm damage (wind and snow) were also reviewed, with a focus how silvicultural practices influence this (Mitchell, 1995; Ruell, 1995). The risk of root and butt rot infestation of spruce by the *Heterobasidion ssp.* fungus, especially during thinning operations, causes significant economic losses in Scandinavia. Mitigation efforts, comparing different stump treatment options and modified silvicultural measures were reviewed and compared for efficacy (Berglund & Rönnberg, 2004; Johansson, Pratt, & Asiegbu, 2002; Rönnberg, Sidorov, & Petrylait, 2006).

Finally, some of the potential losses resulting from the machine harvesting of stands during thinning operations were reviewed. The studies review the permanent loss area dedicated to growing trees by the establishment of striproads (Wallentin, 2007) but yield losses are inconclusive due to the improved growth for trees bordering the striproads (Eriksson, 1987; Mäkinen, Isomäki, & Hongisto, 2006). Mechanical damage during falling, primary processing and forwarding were reviewed.

2.2 The semi-structured interview process

Interviews with important stakeholders and regulators of Swedish forestry were conducted in April and May 2012. A semi-structured interview process (SSIP) was used, facilitating dialogue between interviewer and interviewees. The SSIP is considered a formal interview with set themes to address but without fixed questions, which unfold in a natural manner (Longhurst, 2010). Questions adapt to the context of the conversation and may change between individual participants. Some advantages of this method are:

- A positive rapport is established between interviewer and interviewee
- Depth and details are typically better than fixed-question interviews
- Complex questions can be addressed
- Topics overlooked by the interviewer can surface during the interview process (Sociology.org, n.d.-a).

There are also disadvantages to this method:

- The skills of the interviewer to adapt to the conversational nature of the interview and pose relevant questions
- The interviewer may give cues to solicit a specific answer
- Data analysis is complicated
- Interviewees are asked slightly different questions (Sociology.org, n.d.-b).

Four formal interviews were conducted, while less formal conversations related to the topics addressed during the interviews process were had with other stakeholders. Two private forest companies (Södra and SydVed), two forest owners association (Södra and Mellanskog), a private forest owner (Anders Andersson), the state owned forest company (SveaSkog) and the Swedish Forest Agency (Skogsstyrelsen) were questioned. Commercial interests represented were predominantly those of middle and southern Sweden, while the Swedish Forest Agency and the state owned company SveaSkog have jurisdiction and interests across Sweden.

No Finnish stakeholders were interviewed because the decision to include Finnish thinning practices in the review came after the interview process was completed. Dr. Per-Magnus Ekö introduced me to the different stakeholders and he suggested those located in Southern Sweden to avoid extra travel when possible. The goal of the interviews was to get a sense of the importance of commercial thinning to various stakeholders. The results speak to this effect: that thinning is ubiquitous in Swedish forest management. Similar results are expected in Finnish forestry, based on the similarity in forest management practices.

2.2.1 Stakeholders interviewed for the project

I interviewed Magnus Petersson, who is currently the Forest Technology Manager at Södra. Södra is a forest owners association representing over 51 000 “family” forest owners (non-industrial forest owners) in Southern Sweden. Södra has four core areas: sawn goods (dimensional and specialty), pulp, interior products and biofuels. Mr. Petersson works with developing and testing new technologies, and ensures that forest owners manage their forest according to best practices, including thinning based on Södra standards.

SveaSkog is the state-owned holding ca. 14% of all productive forest land in Sweden. The largest portion lies in the north, but they hold interests in middle and southern Sweden as well. SveaSkog has no forest industries, but is the largest provider of sawn, pulp and energy wood to private industries in the country. I conducted interviews with two SveaSkog representatives. Marie Larsson-Stern is the Vice President of Silviculture, with extensive knowledge on the subject. Fredrik Klang, who is currently the head of marketing for Southern Sweden, started as the Forest Productions manager for the Växjö region of Southern Sweden. Mrs. Klang’s PhD thesis was is silviculture with a focus on thinning.

I interviewed Erik Sollander from the Swedish Forest Agency “Skogsstyrelsen”. Mr. Sollander is working with moose and deer browsing issues, and is a forest policy analyst for the agency. Skogsstyrelsen ensures that forest policy represents all stakeholders (eg. Recreational and production goals), compiles and publishes a yearly volume on forest statistics, and evaluates and revises forest policy.

Leif Olofsson is the managing director of SydVed, a company wholly owned by Stora Enso. SydVed is the self-proclaimed “Thinning Company”, a contractor providing high-quality and cost-efficient first and second thinnings (no final harvests) to private forest owners. They specialise in standing timber purchases because their efficient harvesting allows SydVed to capture profits with this contract method. Stora Enso purchases all of SydVed's timber to feed their Swedish pulpmills.

Anders Andersson is a private forest owner in the Skinnskatteberg region of Västmanland. He now owns 270 ha, which have been owned and managed by his family for generations. Thinnings are particularly important for small forest owners because it is the first income generated after a long period of investments in stand establishment, and because of the smaller management areas there may not be stands currently available for final harvests. Mr. Andersson is a member of the Mellanskog forest owners' association.

Thomas Broström is a forest inspector working for the Mellanskog forest owners' association. He assists owners in creating management plans for their estates, establishing the timing of harvesting operations including thinnings, and visits sites post-harvesting to ensure harvesting and environmental targets are met and that fair prices are paid to the forest owners.

2.2.2 Themes addressed during interview process

The following is the interview guide, some questions being more relevant to some stakeholders than to others.

Thinning programme

1. What is your thinning regime for pine and spruce in southern Sweden?
    - Thinning intensity and frequency?
    - What volumes do you expect from thinning?
2. How do removals from thinnings contribute to the timber supply of your organization?
3. Over a stand's life, what would be the assortments of fuel/pulpwood and sawlogs? Does thinning influence this, and how?
4. How important is PCT when it comes to the first thinning? Are all your stands PCT.
5. Does thinning contribute to a positive economy? In which ways might thinning contribute positively?
    - Early access to income from thinning volumes?
    - Quality development of the remaining stand?
    - Better pulpwood/sawlog assortments over the length of the rotation?
    - Current mill requirements for fibre?

It's estimated that growth can be improved by 20% by 2030. Does thinning fit into this?

Technology

1. Your minimum pulp log size requirement is 5cm under bark. Has the limiting factor in economically utilizing small timber been in harvesting or milling?
2. Your Research and Development department is conducting research and experiments on a number of new technologies. How are there findings being introduced into your forest operations?
3. There have been great efficiency gains with the harvester/forwarder and the cut-to-length system. Where do you see as the next great big productivity gains of the future?

Bio-Energy

1. How much "energy timber" is harvested, not counting logging residue?
2. Do you think biofuels will play a greater role in influencing the species selection?
3. Has biofuels taken away from some of the thinning volumes dedicated to pulpwood, or is it mostly just making use of logging residues which were previously un-used?
4. How long has forest-based biofuels influenced forestry decisions? And your economy?
5. Has biofuel sales changed your thinning practices?
6. Do you see bio-energy causing a shortage of pulpwood, or raising pulpwood prices?
7. Has fibre demand for bioenergy changed your operations?
    a. Thinning volumes to bioenergy?
    b. Harvesting of tops and branches?
    c. Stump harvesting?

Tree species selection, exotics, mixed stands and broadleaves

1. Regarding exotic species, do you feel climate change will play a role in the decision making for suitable species?
2. Are certain exotic species currently on your radar for research or commercial plantations?
3. Do you manage *Pinus contorta* (*Pinus contorta* Dougl. var. *latifolia*)? Are there any differences in management between *Pinus contorta* and *Pinus sylvestris*?
4. How do you manage the birch component in a mixed stand?
5. Do you manage any birch or noble broadleaf stands?

Forest Certification

1. Are you receiving a premium for your certified wood? Do the benefits outweigh the costs?
2. Do you see a trend in forest certification?
3. What are some special environmental considerations you have to deal with?
4. How has FSC/PEFC changed your logging operations?

Future trends

1. What developments do you see coming in commercial thinning?
    a. Fewer thinning?
    b. No thinning?
    c. Shorter rotations?
    d. Other developments?

2.3 Gavin Lake Case Study

2.3.1 Physical description of the study area

The Gavin Lake block (6 315 ha) of the Alex Fraser Research Forest is located in the Beaver Valley in the Interior of BC (lat.: 52,45 N, lon.: 121,72 W). Elevation ranges from 690 m to 1250 m ASL. “The western part of the block is influenced by a drier and warmer, montane boreal climate (represented by the Sub-Boreal Spruce biogeclimatic (BEC) zone), while the eastern part of the block is influenced by a wetter, cool temperate climate (represented by the Interior Cedar Hemlock BEC zone)" (Klinka et al., 2004). Precipitation and temperature increase following the West-East gradient.

Interior Douglas fir (*Pseudotsuga menziesii*), lodgepole pine and trembling aspen (*Populus tremuloides*) can form pure stands, while the majority of the block is made up of mixed-species stands. The block is dominated by Douglas fir, (3 222 ha, 56%). Hybrid spruce (*Picea glauca* X *engelmannii*) is located throughout the block, most present in cool and wet sites (908 ha, 15%). Historically, lodgepole pine was scattered throughout on poorer sites (555 ha, 9%) occurrence is rare due to the MPB. Western red cedar (*Thuja plicata*) can be found in the eastern part of the block in the ICH zone (510 ha, 10%). Balsam fir (*Abies lasiocarpa*) forms a small component of mixed stands, while a few broadleaf species occur along wet depressions and as scattered individuals (trembling aspen, *salix ssp.*, black cottonwood (*Populus trichocarpa*), birch (*Betula ssp.*) and mountain alder (*Alnus tenuifolia*) (Klinka et al., 2004).

A large portion (ca. 2 200 ha) of the Gavin Lake block was regenerated by fire in the early 1920's and created a number of stands that are currently at different developmental stages of stand conditions. This area is the largest mostly intact area of the AFRF, as the more recent harvesting has been outside the fire perimeter. The goal of the study was to classify the undeveloped subset into various stand conditions, to collect stand inventory information and to prescribe recommended treatments for each distinct stand, with a particular interest for commercial thinning opportunities.

2.3.2 Treatment unit classification

A variety of GIS tools and field reconnaissance were used to classify the treatment units. Available GIS tools were:

- High resolution orthophoto (Appendix 2: Figure 27)
- LIDAR tree height data (Appendix 2: Figure 28)
- 2 meter contour maps (Appendix 2: Figure 29)
- Digital Elevation Model (Appendix 2: Figure 30)
- Hydrological maps (Appendix 2: Figure 29)

The first step was conduct field recce to ground-truth the GIS information. This was done by conducting transects and noting stand conditions as seen in the field. Transects lines were 200 m apart, following a path using map and compass. At the end of the line, a GPS reading was taken to correct for deviations. Stand conditions were recorded every 50-100 m along the transect, depending on variability of the forest. A total of 320 ha were surveyed in the field. After the field recce, it was possible to classify the remaining portion of the study area using the GIS tools.

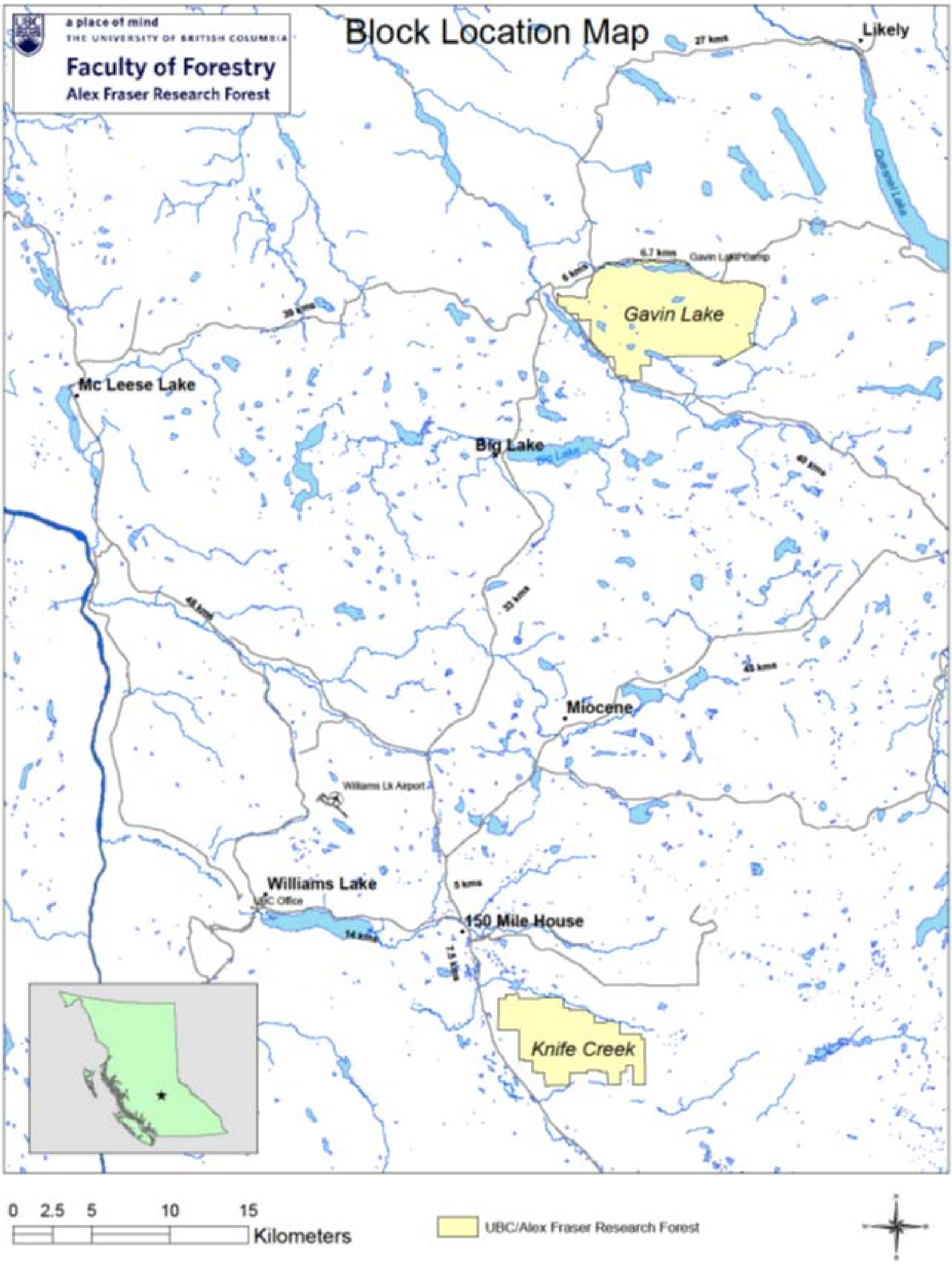


Figure 2 - Location of the Knife Creek and Gavin Lake blocks of the Alex Fraser Research Forest in British Columbia, Canada (Alex Fraser Research Forest, 2007)**.**

2.3.3 Classification scheme and recommended treatment

The study area had previously been separated in legal compartments used for communicating harvest plans with the provincial government and served as boundaries in First Nations archeological surveys. The classification scheme of this project aims to create new block boundaries based on the similarity in forest condition. Six treatment classes were identified and used, representing the gradient from mature to immature forest and that which should be protected. Each unit was classified and a specific treatment prescribed; certain units in the middle stages of stand growth were also given secondary treatment options to indicate to the AFRF manager a certain flexibility in forest planning. A guideline was to have units of at least 5 hectares in size, to avoid micro-managing stands. Table 2 describes the classification and its associated treatment.

Table 2 - Each unit was classified into one of six classes, each class with a recommended treatment representing the gradient of forest conditions found. Certain units had a second classification and treatment as an option.

Classification	Recommended treatments
Mature	Ready for final harvest
Near-mature	No spacing required before final harvest Wait before final harvest
Middle-aged	Thinning from below
Immature	Wait before first entry Potential future thinning opportunity
Shelterwood	Logging to initiate shelterwood regeneration
Protection	No treatment

Units were classified both by stand characteristics (Table 2) but were also given a priority ranking. A stand bordering another with the same prescription was placed in a separate unit if the two had a different priority ranking. The priority ranking indicates the likelihood of a unit moving to the next stage of stand development.

Table 3 – Every treatment unit was giving classified by stand condition and by priority ranking, an indication the likelihood a unit would change treatment class.

Priority	Description
Priority 0	Unit that recently entered a new treatment class (eg. a new clearcut) Protection forest, no management required Not a priority
Priority 1	Unit with recent change of treatment class Protection forest, no management required Low priority
Priority 2	Monitor market conditions (small timber) Consider treatment based on adjacency to other stands Low SI stands with slow growth and slow change in treatment class
Priority 3	Move to planning phase Storm damage may be present Likely to become Priority 4 in the future
Priority 4	Move to operational planning Stands at high risk from storm damage or significant self-thinning Windthrow may be present with salvageable wood

2.3.4 Criteria for thinning – Decision making support tool

Thinning guidelines are well established in Sweden and Finland and tools assisting the decision making process are generally understood by foresters, and readily available in the public domain for local species (Skogforsk offers a simplified model on its website http://www.skogforsk.se). The Scandinavian thinning guidelines suggest a course of action and model the results. Stand density management diagrams (SDMD) are a tool used (in British Columbia) to obtain a general prediction of yield at final harvest based on different spacing prescriptions (thinnings). SDMD are most useful for pure stands in planted forests (similar to Finland and Sweden), and did not produce adequate decision making support for this project. Instead a decision making tree based on AFRF management objectives was developed to assess for thinning. Management objectives were:

- Piece size and volume removal (with 35-40% BA removal from below)
    - Minimum (target) removal of 80 – 100 m^3/ha
    - Minimum log dimension of 3,76 m length and 11,4 cm top
- Consider second entry where appropriate
- Aim for final harvest of ca. 400 - 600 quality st/ha
- Target thinnings in Douglas fir leading stands
- Target thinnings with where
    - quality, straight in residual stand and
    - where uniform spacing possible in residual stand
- Consider early thinnings in stands where canopies are starting to differentiate
- Target thinnings in stands with differentiated canopies, where natural mortality likely to occur
    - Focus thinnings in stands with significant merchantable standing dead timber
- Thinning in stands in rapid height growth phase (middle-aged and immature)
- Thinning in mature and near mature stands to address age-class distribution issues, where appropriate
    - Thinning where H:D ratio can be kept below 0,8
    - Avoid thinning where stability issues (windthrow) apparent
    - Consider initiating the shelterwood regeneration method in mature stand

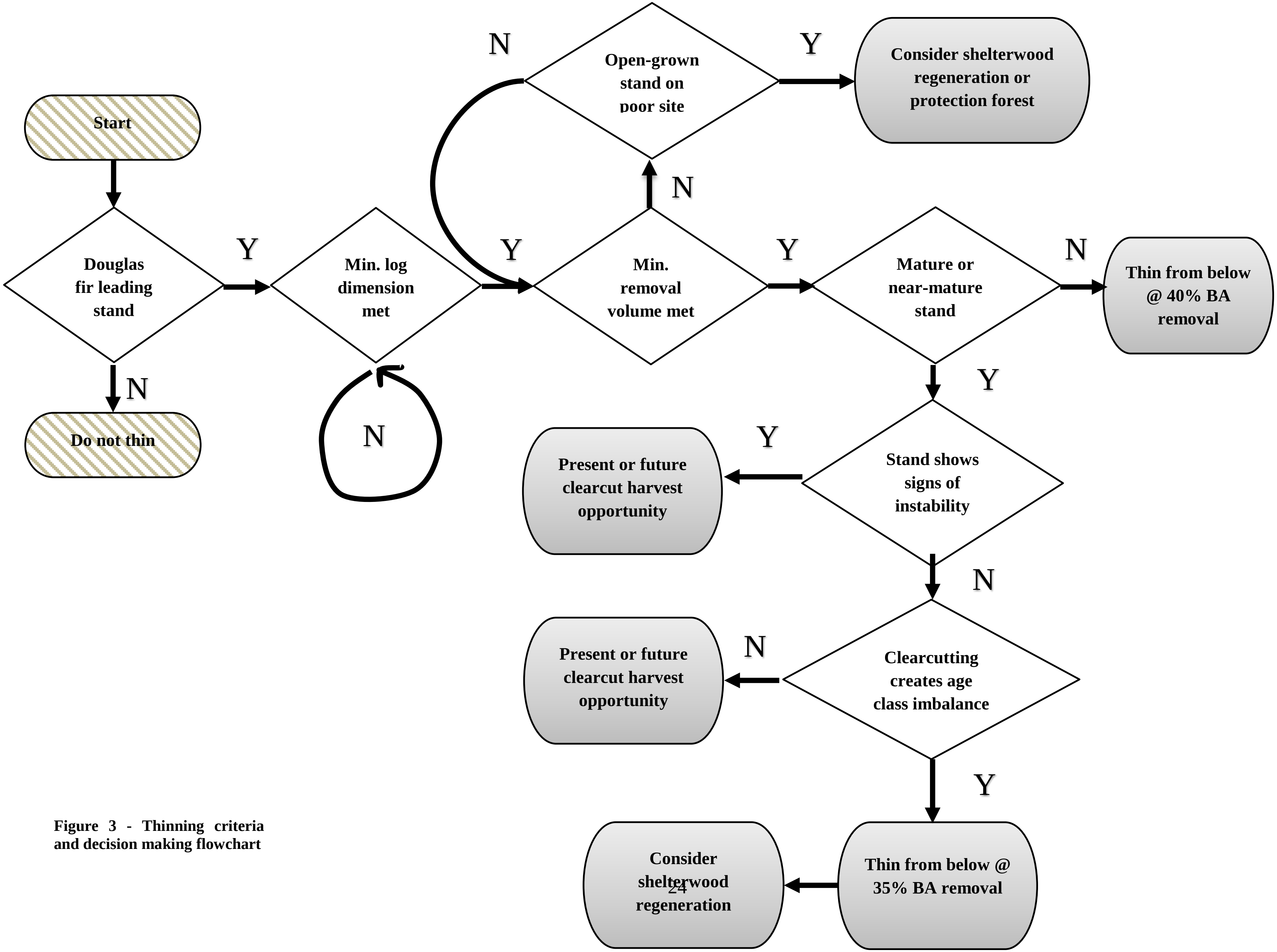


Figure 3 - Thinning criteria and decision making flowchart

2.3.5 Stand inventory data collection and survey design

A non-systematic cruise design was used to gather the stand inventory data. The cruise design and the stand inventory information were collected according to AFRF specifications, and all inventory data collected for this project will be added to the AFRF databases.

2.3.5.1 Cruise design

A non-systematic cruise design was used, in order to capture the variability within the different units and take into account a unit's priority level. Large or high priority units had more survey plots than small and low priority units. The survey plot locations were randomly placed to record the leading condition for each unit. Those units with variability in stand conditions would have another survey plot to capture this variability. Just under half (26 of 60 plots) of the plots were surveyed the previous summer (2011) as part of ongoing stand inventory information gathering for the AFRF. Their locations also attempted to capture the variability in stand conditions, however they used the legal stand boundaries and not the newer unit boundaries. The remaining plots (34 of 60 plots) were surveyed as part of this research project (summer 2012), following the same guidelines and contributing to the AFRF inventory.

2.3.5.2 Cruise plot locations

At each survey plot, information was gathered from five cardinal plots. GPS coordinates for the centre plot (CP) were established according to the cruise design. From CP, the four other plots were located 50m away in each cardinal direction (N-S-E-W). No correction was made for slope distances, and in most cases the slope was not significant to affect the horizontal distance. If two or more of the plots were not representative of the average stand condition (Eg. The plot centre falls in a stream or a patch of bare rock), the CP plot was moved 50 m in the opposite direction of the closest block boundary.

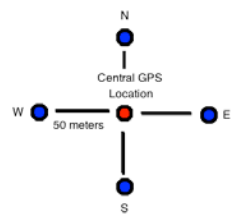


Figure 4 – Cluster plots are 50 m away from the central plot. The central plot location is randomly selected.

2.3.5.3 Data collection

At each plot centre, a variety of information was collected focussing on timber values (no information on biodiversity or other values was collected). A wedge prism with a basal area factor (BAF) of "4" was used to establish which trees were included in the variable-area plot. "In" trees must belong to the dominant tree size class (DBH > 12,5 cm), which is based on merchantable tree size for the research forest. Information collected for all "In" tress was: Species, DBH, Quality. Additionally, Age and Height was measured for one tree per plot (five total for each plot cluster). The criteria for tree selection of Age and Height measurement was a dominant or co-dominant position in the canopy. An attempt was made to capture trees from the smallest to the largest diameter and height classes to develop acceptable Height to DBH curves were created to estimate height of non-measured trees. Wolf trees, trees with double tops or trees with broken tops were omitted as candidates.

2.3.6 Limitations

Limitations exist in the analysis of the Gavin Lake data. The GIS data used for the classification was gathered in 2010. There were two instances of recent harvest blocks that appeared as mature forest using the GIS tools. There was a large patch of windthrow that was discovered during the field recce that did not appear on the GIS. These three instances were corrected with the field recce and information from AFRF managers, but it is possible that small pockets of disturbances were not properly identified. However, due to units being a target minimum of 5 ha, it is most likely that unless the disturbances were very large, the unit will still have been properly assessed.

The tree heights used in the analysis were based on regression equations built with the stand inventory information aggregated by treatment classes, correlating DBH (measured) to heights (calculated). Studies have shown that diameter is not directly correlated to height, but sufficient equations were developed for AFRF management goals.

Mature:

$$height = 5{,}358\, dbh^{0{,}4595} ;\ R^2 = 0.53748 ; n = 111$$

Near-Mature:

$$height = -0{,}0007dbh^2 + 0{,}4464dbh + 11{,}917 ;\ R^2 = 0.68765 \ ; n = 25$$

Middle-Aged:

$$height = 9{,}7112ln^{dbh} - 9{,}9774 ;\ R^2 = 0{,}55867 ; n = 88$$

Immature:

$$height = 2{,}8215\, dbh^{0{,}6209} ;\ R^2 = 0.74073 ; n = 38$$

Protection forest:

$$height = 14{,}551ln^{dbh} - 28{,}274 ;\ R^2 = 0{,}81497 ; n = 10$$

Shelterwood:

$$height = 0{,}0143dbh^2 - 0{,}1797dbh + 12{,}808 ;\ R^2 = 0.61656 \ ; n = 19$$

Volume estimates were based on a simple cone formula. Conical estimates of tree volume tend to underestimate volume for trees with a more cylindrical shape, and should be considered an acceptable, but conservative estimate of tree volume in the absence of local stand tables (Steen Magnussen & Reed, 2004).

The assessment for priority was based on objective and subjective criteria. Current stand characteristics and the likelihood of the stand condition changing in the near future (0-10 years) was the primary criterion. However, some considerations for proximity to existing roads and/or ease of access were included for management purposes.

3 Results

3.1 Literature review

3.1.1 The effects of thinning on growth and yield

Swedish and Finnish studies on growth and yield with regards to thinning were reviewed. The reports study the effects on gross and net yield of Scots pine and Norway spruce. Various thinning regimes were compared, the most common being thinning from below with light (0-25% BA removal), medium (25-45% BA removal) and heavy intensity (up to 70% BA removal) with one to three treatments throughout the rotation. Some studies also included thinning from above and delayed first thinning in their analysis. The Finnish studies follow the light/medium/heavy BA removal guidelines above, while the description on the Swedish thinning regimes are presented in Table 4 below.

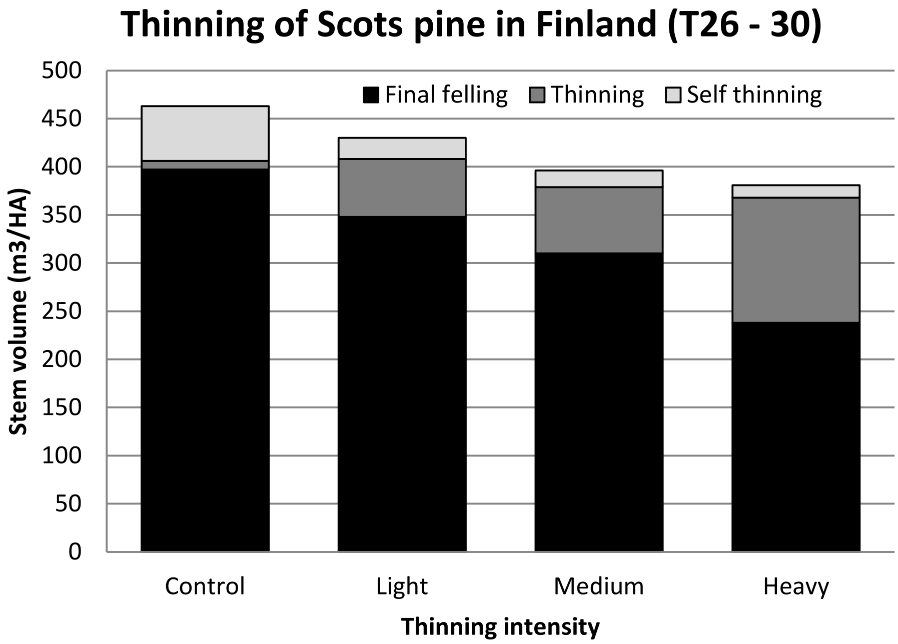
Table 4 - Description of thinning regimes of the Swedish studies, as labeled in Figure 4 and Figure 5.

Tree species	Label	No. of thinnings	BA after thinning	Thinning grade of 1st thinning
Scots pine	A(3:18)	3-4	18	25
	B(2:15)	2	15	43
	C(1:10)	1	10	60-63
	D(3:13)	3-4	13	50
Norway spruce	A(4:28)	4-6	28	20-25
	B(2:23)	2-3	23	40-43
	C(1:12)	1	12	63-70
	D(4:20)	4-6	20	40-50

All studies reviewed found decreasing total yields with decreasing density. (Mäkinen, Hynynen, & Isomäki, 2005; Mäkinen et al., 2006; Nilsson et al., 2010). The unthinned control plots had higher gross volume production while heavily thinned plots had the lowest gross yield. Within a range of light thinning intensities, yields were lower but similar to unthinned plots, especially in spruce. This is in contrast to the individual stem diameter, which is inversely proportional to stand density for both species.

Most studies reviewed report no marked difference in spruce net yield between control and approximately 35% BA removal in two thinning treatments performed from below (Figure 5) (Mäkinen et al., 2006; Mäkinen & Isomäki, 2004a; Nilsson et al., 2010). In contrast to spruce, reports show net yield losses in Scots pine of between 0 and 20% with similar thinning frequency and intensity (Mäkinen et al., 2006; Mäkinen & Isomäki, 2004c; Nilsson et al., 2010). However, in Scots pine stands where thinning is carried out, there is little effect on growth or yield between the different thinning regimes (Figure 4). The difference in shade tolerance between the two species likely explains much of this difference. Shade tolerant Norway spruce, whose crown has not receded as far up the stem as intolerant Scots pine, can more rapidly make use of the space freed up during spacing (Mäkinen & Isomäki, 2004b).

In spruce, frequent, light thinnings performed from below have shown to marginally increase total yield (in: Nilsson et al., 2010). However, the results from these studies were relevant to the thinning practices of the early 20th century, and the high frequency and low intensity of these thinning programmes are no longer practicable with the mechanisation of harvest operations.



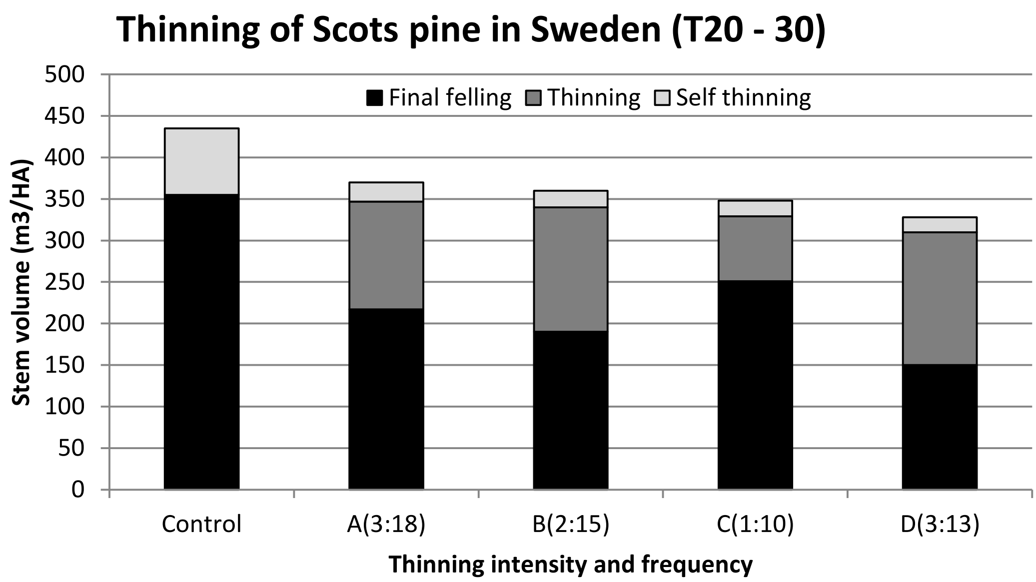
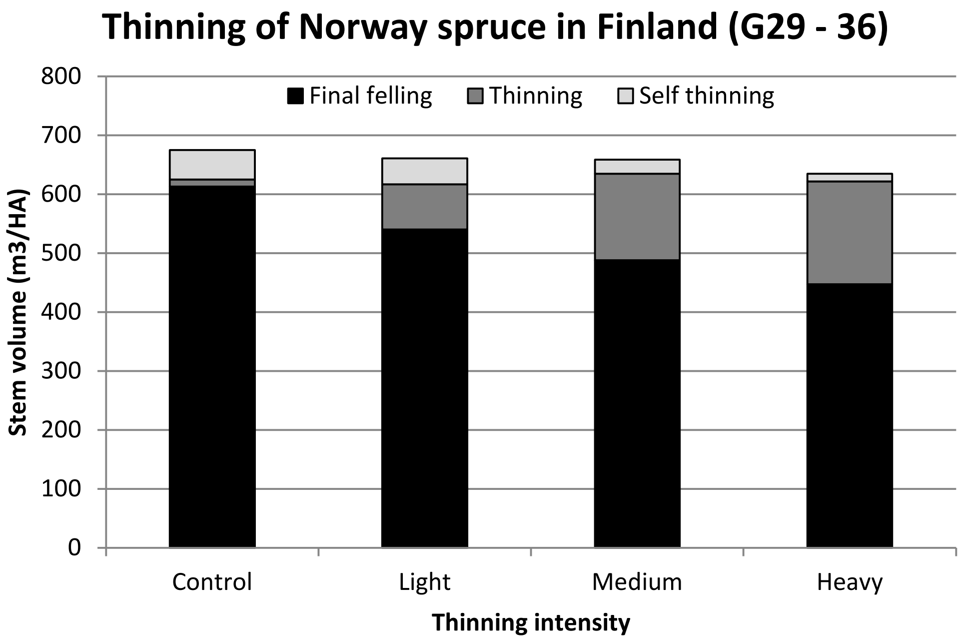


Figure 5 - Thinning of Scots pine reduces total yields by 0 - 20%, but there is only marginal differences in total yield between the different thinning programmes. See Table 4 for label explanations (Top figure: Mäkinen & Isomäki, 2004b; Bottom figure: Nilsson et al., 2010)**.**



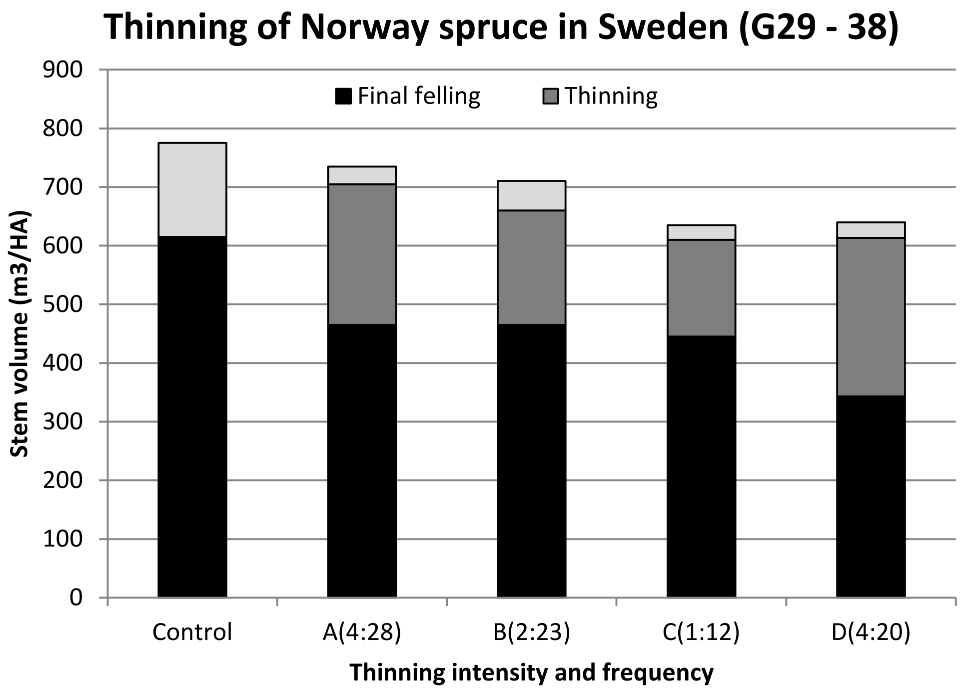


Figure 6 - Thinning has very little effect on total yield in Norway spruce. Only repeated heavy thinning reduces total yields. See Table 4 for label explanations (Top figure: Mäkinen & Isomäki, 2004a; Bottom figure: Nilsson et al., 2010)**.**

It can also be useful to divide "merchantable wood" into pulpwood and sawlog assortments. Heavy thinning reduces total yield, but a larger proportion and volume of timber is in the sawlog assortment (Nilsson et al., 2010). Medium thinning produces similar log volumes as the control, but most of the pulpwood has been removed during thinnings, as opposed to a final harvest. The control plot had a higher total yield but more than half of this volume was pulpwood (Mäkinen et al., 2005). A Finnish study reports that higher sawlog yield, lower pulpwood yield, less waste at final harvest and the benefit of some volume produced before final harvest were achieved with a thinning intensity of 33%

BA removal (from below) in Scots pine and Norway spruce, with marked diameter increases in logs removed at final harvest and minimal effect on gross volume (Figure 6) (Mäkinen et al., 2006). In the control plots, one quarter of the trees were dead in Scots pine stands and one fifth in spruce stands compared to almost no mortality in thinned stands. “The minimum length applied for pulpwood boles was 3.0 m, and the minimum top diameter was 7.0 and 8.0 cm over bark for Scots pine and Norway spruce, respectively. The stem wood below this size was considered as waste wood. The minimum lengths applied for logs were 3.1 and 3.7 m, and the minimum top diameter over bark was 20.5 and 19.5 cm for Scots pine and Norway spruce, respectively (Mäkinen et al., 2006).

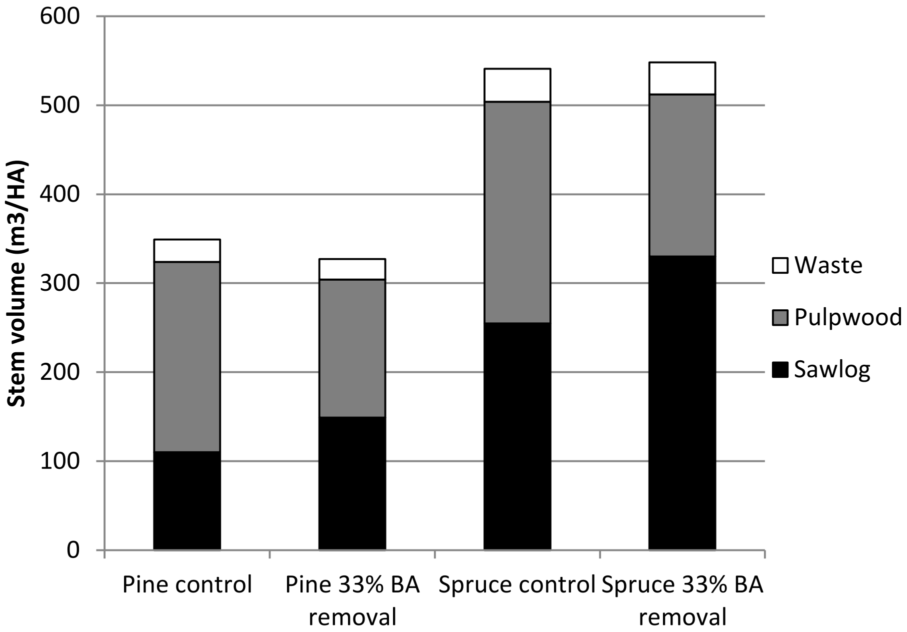


Figure 7 – Thinning has little effect on net volume but can favourably influence the proportion of sawlogs produced throughout the rotation. Sawlog volumes increase by 35,5% for Scots pine and 29,4% for Norway spruce (Mäkinen et al., 2006)**.**

3.1.2 The effects of thinning on individual tree diameter and volume

Accelerating the diameter development of individual trees is one of the primary goals of modern thinning programmes. The merchantability of a stand, or the length of the rotation, is related to the average diameter of individual stems, which also affects which products trees can be processed into. Thinning has the ability to shorten the amount of time required to reach sawlog dimensions, the most economically valuable log assortment. The effects of thinning on growth and yield were reviewed above. In Scots pine, unthinned plots always had higher gross yield while lightly thinned plots of Norway spruce had equivalent yield. This is in contrast to stem diameter, which is inversely proportional to stand density.

All studies reviewed showed increasing diameter and individual tree volume increment with increasing thinning intensity (thinning from below). Table 5 shows results comparing light, medium and heavy thinning from below with thinning from above for Norway spruce. In all instances except thinning from above, thinning significantly increases individual log size, the largest effects produced with the heaviest thinning intensity.

Table 5 - The effects of thinning on average tree diameter shows increasing diameters with increased thinning strength, except for thinning from above which removes lager stems during thinnings (Taylor & Pape, 1999)**.**

Treatment	Number of thinning	BA removed at 1st thinning	Form	Diameter after final thinning
Light	5	20	Below	250
Medium	3	40	Below	260
Heavy	1	70	Below	284
Above	6	20	Above	192
Control	0	0	Control	194

When the aim of the management is creating sawlogs, the heavy thinning reduced a Scots pine rotation by 16 years compared to the control, in a Finnish thinning study. (Mäkinen, Hynynen, et al., 2005). The lower total yield from the heavy thinning compared to the "no-treatment" option could be made up by a shorter rotation.

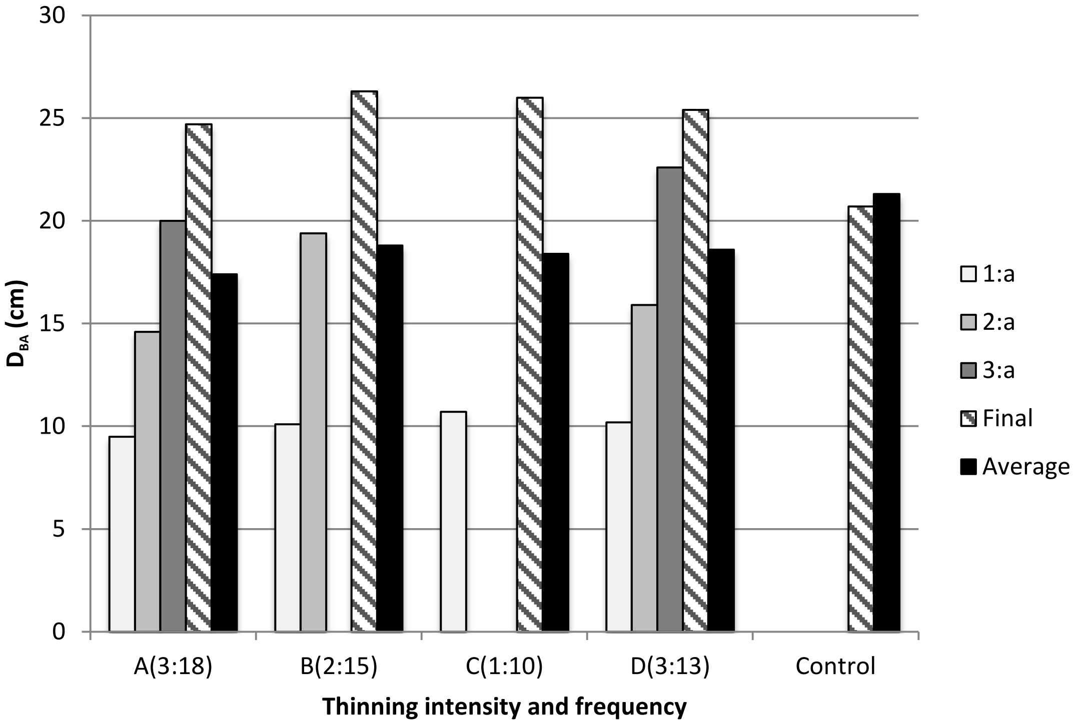


Figure 8 - Average DBH weighted by basal area of Scots pine removed during thinnings, at the time of final measurement and overall total. See Table 4 for label explanations (Nilsson et al., 2010)**.**

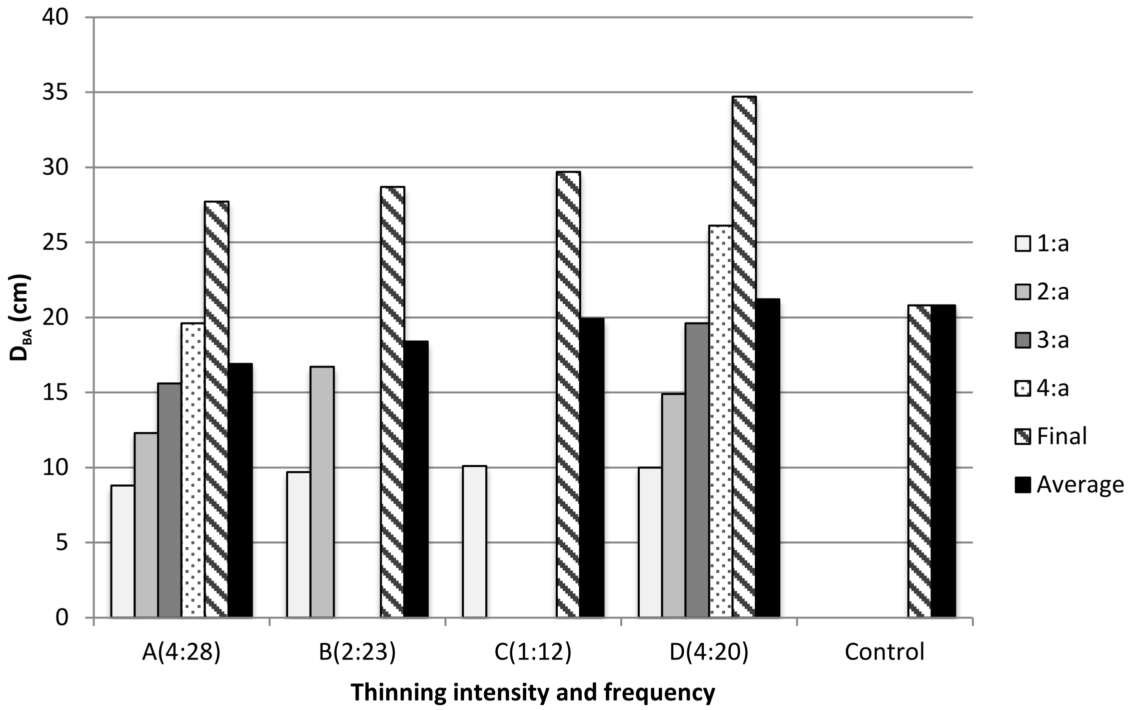


Figure 9 - Average DBH weighted by basal area of Norway spruce removed during thinnings, at the time of final measurement and overall total. See Table 4 for label explanations (Nilsson et al., 2010)**.**

3.1.3 The effects of thinning on tree quality

Thinning affects the quality of the final crop through one of two mechanisms: the selection process and residual tree growth. While it might not be possible to completely separate the effects of the two mechanisms, a distinction between the two is useful. Furthermore, thinning regimes cannot be considered in isolation of previous stand characteristics. The pre-thinning stand density affects early stem development, the number and intensity of thinnings required and the availability of choice stems for selection.

A list of quality metrics facilitates the discussion on the effect of thinning on quality development:

Tree form

- Deformation in lower log (tree not cylindrical)
- Leaning tree
- Crooked tree
- Wolf trees with bad quality
- Stem taper

Stem defects

- Double stems
- Spike knots
- Stem cracks

Branching characteristics

- Spike knots
- Knots, size and frequency
- Branches, quantity and diameter of thickest branches

Wood properties

- Crown formed (Juvenile) wood
- Stem formed (Mature) wood
- Clear wood (knot free)
- Wood basic density
- Grain angle

Physical damage

- Dead, dying or heavily suppressed (expected to die)
- Felled trees
- Stem breakage
- Stem wounds

Biotic damage

- Fungi damage
- Insect damage
- Canker
- Root rot

The effects of thinning on tree form and stem defects result largely from the selection for removal of poor stems during PCT and first thinning. Poorly formed stems and those with obvious defects are removed first, resulting in stand with a high proportion of quality stems. Long and straight stems are recognized as being more valuable, other properties being equal (Wallentin, 2007). Thinning intensity has a positive relationship with stem taper (Mäkinen et al., 2005), thus reducing this measure of quality. Experiments where a single heavy thinning (60-70% BA removal) was compared to more frequent lighter thinnings showed that the less extreme treatments decreased the taper. Differences in taper were greater with early onset of thinnings, and on richer sites, for both Scots pine and Norway spruce (Mäkinen & Isomäki, 2004a, 2004c).

Branching characteristics are largely affected by initial stand density and by PCT, but thinning can also influence these measures of quality. Again, the removal of poorly formed stems increases the quality of the residual stand. But here tree growth following the thinning plays a role. If crown recession has started, the branches in the lower log will not be influenced by the thinning (Pfister, Wallentin, Nilsson, & Ekö, 2007). But when crown recession has not started, the thinning will slow crown recession, and living branches will increase in diameter. Studies show decreasing stand densities have lower height to live crowns, (Pfister et al., 2007; Ruha & Varmola, 1997), and thus larger branches may develop.

Thinnings affects growth rates of individual trees, which have an effect on wood properties. The ideal log is cut from clear, knot free stem formed wood with high basic density (low growth-ring width). In managed forests, the thinning practices tend to increase diameter growth, increase ring-width and decrease wood basic density (Taylor & Pape, 1999). However, factors besides basic density may be more important in determining the quality of a tree. Crown formed (Juvenile) wood is formed under the influence of the tree's crown, while stem formed wood is formed after the crown has receded. The properties of crown and stem formed wood differ; crown formed wood has many properties considered undesirable to the forest industries (Wallentin, 2007). Thinning increases diameter growth and slows crown recession, thus increasing the amount of stem-formed wood *at some point along the stem*. If the lowest part of the living crown is above the lower log (the most valuable part of the tree), this will have no effect on the amount of stem-formed wood in this region. Thinning from above throughout the rotation will reduce the stem-formed wood more than thinning from below, but only when the stand is left to reach the same final diameter (Pape, 1999).

Physical and biological damage can be affected be different thinning regimes. The largest physical damages relate to stand stability issues (wind and snow damage) and machine-cause damage, reviewed in Section 3.1.4 and 3.1.6 of this paper. The biological damages relating to tree quality, mainly root and butt rot, are reviewed in section 3.1.5 of this paper.

A delayed thinning can affect quality in a number of ways. If conducted after stem differentiation, it might be impractical to remove a poor quality stem if it has already suppressed its neighbours

(Nilsson et al., 2010). Thinning larger stems increases brushing wounds during logging operations, and creating sites of infection by biotic agents. A remedy for this may be to select poor stems for initial removal, and complete the negative selection process by targeting stems damaged in the initial logging. In the tree/stand quality metrics reviewed, stem-selection had significant effect on future crop quality, which might not be as pronounced with a delayed first thinning.

3.1.4 Risk of wind and snow damage

There are two types of wind damage: endemic windthrow and catastrophic windthrow. Catastrophic windthrow is caused by major storms with unusually high wind speeds, where silviculture prescriptions have little influence on the extent of the damage. Endemic windthrow is that caused by normal wind speeds and wind direction, where small windthrow pockets are created by storms and gradually grow from the edges over time (Ruell, 1995). Catastrophic windthrow receives much attention due to its destructive nature, while endemic windthrow receives much less attention, even though forest stands can be helped or hindered through silvicultural measures and forestry operations such as thinnings.

Certain stand characteristics render the stands prone to wind or snow damage. Windthrow hazard is a combination of “Stand”, “Exposure” and “Soils” (Mitchell, 1995). Site characteristics explain much of the storm (snow and wind) risk associated with a stand (Valinger & Pettersson, 1996). However, there remain silvicultural practices that can affect the “Stand” and “Exposure” risk levels. In a climate such as Sweden or Interior BC with mild summers and harsh winters, wind and snow effects usually act in conjunction. There are, however, differences in stand characteristics prone to each particular damage agent.

In widely spaced stands, trees have high stem taper, and a low height to diameter ratio (H:D) and are individually resistant to windthrow (Päätalo, Peltola, & Kellomäki, 1999). Unmanaged stands typically have lower stem taper, individual stems have little resistance but instead rely on neighbouring trees (ie. “stand effect”) for stability (Mitchell, 1995). However thinning per se increases windthrow risk, therefore the smallest damages are often found in unthinned stands. Thinning increases stem thickness and lowers the H:D, making the stands windfirm, in the long-term. A thinning programme of 25-40% BA removal in *young* forests typically helps protect against storm risks (Valinger & Pettersson, 1996). Heavy thinning, which although has the greatest positive affect on stem taper, increases wind exposure to a point where the stand is less windfirm. The forces within a closed stand are as low as 25% of actual wind forces (Ruell, 1995). Unthinned stands can be very windfirm, until endemic windthrow starts. Once commenced, these stands are at greater risk than regularly thinned stands due to their tall and slender shape (Valinger & Pettersson, 1996). Old stands, who have reached their top height and are only putting on diameter growth, have adapted to the wind forces acting upon them and are generally resistant to windthrow (Valinger & Fridman, 2011).

Stands, whether thinned or unthinned, exhibit greater risk of windthrow with age. Thinned stands are particularly vulnerable immediately following the thinning, but eventually become windfirm (taking ca. five years) and have similar risks to unthinned stands. Later thinnings leave stands more vulnerable, and for a longer period of time, compared to unthinned stands, as is anecdotally represented in Figure 9.

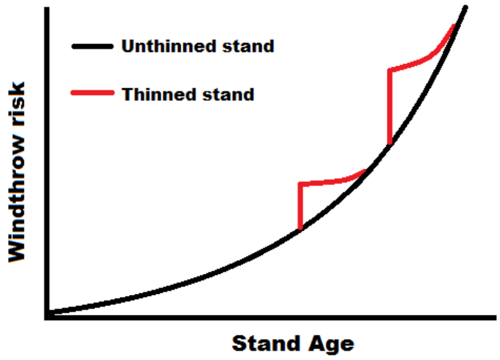


Figure 10 - Risk of windthrow increases with stand age and immediately after thinnings. Later thinnings pose a greater risk and take longer for the residual stand to become windfirm again.

Dense, unthinned stands or those thinned from above are particularly vulnerable to snow damage. Heavy thinning greatly reduces the risk of snow damage, but at the expense of high wind damage risk. Stands of medium thinning intensity are at a reduced risk of snow damage, and are acceptably resistant to wind damage, presenting the best option to managers (Valinger & Pettersson, 1996).

For practical forest management, early thinning to windfirm the stand when trees are small and flexible, is the recommended prescription. Trees will develop with good H:D and should be resistant against endemic storms throughout the rotation. Late thinning in mature stands can have disastrous effects (Ruell, 1995). Studies report that thinned stands are vulnerable 2-5 years after thinning, but potentially up to 10, depending on how quickly crown closure occurs (Mitchell, 1995; Valinger & Fridman, 2011). Early thinning helps to reduce the period of high vulnerability, by starting good diameter development and tapering at a young age (Pellikka & Järvenpää, 2003). No thinning should occur in dense stands with tall and slender stems where endemic windthrow has begun (Mitchell, 1995). Edge trees are the most exposed to wind forces and once they have stabilised, care should be taken to retain the same edge until the end of the rotation. New edges should not be created adjacent to recently thinned stands, to reduce exposure during the vulnerable period after thinning.

3.1.5 Risk of root and butt rot infestation

Root and butt rot in Norway spruce, mainly caused by the *Heterobasidion ssp*. fungus (*Heterobasidion annosum* and *Heterobasision parviporum*), is responsible for large economic losses in Scandinavian forests (Berglund & Rönnberg, 2004). Losses are created by the downgrading of timber, and by the slower growth rate exhibited by heavily infested stands. Heavily infested stands are also more vulnerable to windthrow (Oliva, Samils, Johansson, Bendz-Hellgren, & Stenlid, 2008).

The fungus lives in wood, mostly in the butt of trees or in their roots. Initially, the fungus causes discolouration of the wood, followed by rotting of the tissue. Infected trees still have defense mechanisms thus have a slower rates of spread than stumps (Pettersson, Rönnberg, Vollbrecht, & Gemmel, 2003). This suggests that infected trees should be left growing for the entire length of the rotation (Berglund, 2005). However, detection of an infected tree is almost impossible until the final stages of infection and decay.

Heterobasidion spreads in two different ways. Airborne basidiospores can land on and colonize freshly cut stumps (eg. during thinning) or exposed tissue (eg. from logging machinery damage), thus infecting new stands. If the fungus is already present in a stand, it can infect new trees by spreading through the root network (Bends-Hellgren et al., 1999). Another study shows little correlation between the incidence of Heterobasidion in past and present rotations, suggesting the infections is a result of thinning operations (Rönnberg, 1999).

Treating freshly cut stumps after thinning or harvesting can reduce the risk of infection (Berglund & Rönnberg, 2004; Brandtberg, Johansson, & Seeger, 1996; Rönnberg et al., 2006; Vasiliauskas, Lygis, Thor, & Stenlid, 2004). A biological (*Phlebiopsis gigantea*) or chemical agent (urea, borates, sodium nitries, etc) is applied to the exposed surface and prevents the infection by one of two ways. Stumps inoculated with *P. gigantea*, a competing wood decay fungi, are “occupied” and *Heterobasidion* cannot establish or compete. Chemical agents act as toxins (P-O. Brandtberg et al., 1996), or in the case of urea its reaction to air and subsequent transformation to ammonia raises the pH to a level where *Heterobasidion* basidiospores cannot germinate or survive (Johansson et al., 2002). Application can be manual or mechanised. Both harvesters and chainsaws can be fitted for mechanised applications. The success rates of prevention vary based on the agent used and the application method. Chemical agents are more successful than Rotstop® (the most popular commercial formulation with active ingredient *P. Gigantea*). Chemical agents have proved effective but are no longer used due to environmental concerns. The exception is urea, which is still in used in forest fertilization (Ingerslev et al., 2001) and to a lesser extent in stump treatment.

Certain logging or silvicultural practices, such as winter logging, fewer number of thinnings, earlier thinnings and shorter rotation length can minimize the risk of infection. The production of basidiospores almost ceases in sub-zero temperatures (P-O. Brandtberg et al., 1996). This same study reports a 2% infection rate for logging between November and February, compared with a 34% infection rate for logging between June and July. A thinning experiment measuring the incidence of root rot considers temperatures above 5° C to be the threshold (Rönnberg, Mårtensson, & Berglund, 2008).

The initial spacing, or stand density, affects the risk of infection in two different ways. Heterobasidion can spread from an infected tree of stump via direct root contact and between root graphs (Bends-Hellgren et al., 1999). Densely spaced stands can have more overlapping root structures and higher root contact, increasing the risk of within-stand spread. Initial density also affects the number of thinnings required over the length of the rotation. Decreasing initial stand density should reduce the number of thinnings required, while it may also delay the timing of the first commercial thinning. This reduces the time the fungus is allowed to spread in a stand (the time period between the first commercial thinning and final felling). Combined with a shorter rotation period altogether, this could be an effective method to minimize risk (Bends-Hellgren et al., 1999).

The studies reviewed focus on Swedish and Finnish forests, although Heterobasidion’s range extends beyond Europe and is present throughout the Northern hemisphere. Managers of plantations in Eastern Canada and the Eastern United States have been affected by Heterobasion in their thinning stands (Dessureault, Roy, Laflamme, & Bussières, 2003; Stambaugh, 1989). Eastern North America has a longer history of more intensively managed forests and mitigation efforts there are similar to European measures, predominantly using stump treatment during thinning operations. With a move away from old-growth logging towards managing second-growth forests, Western North America also faces challenges in dealing with Heterobasidon, especially as commercial thinning becomes a common practice. Infections have been recorded throughout the Pacific Coast, from British Columbia to Northern California (Morrison & Johnson, 1999; Stambaugh, 1989). Most conifer species found throughout North America have reported infections by Heterobasion (Stambaugh, 1989).

3.1.6 Machine-caused losses during operations

Strip roads are non-permanent machine corridors located in the harvest block. They allow the harvester to enter the stand and log, while the forwarder can bring the harvest to roadside. Because the PCT is conducted motor-manually without ground-based machines, strip roads are only established at the first thinning. The same strip roads will be used throughout all thinning or storm salvage operations, until the final harvest.

Striproads have the negative consequence of removing a significant proportion of the stand prior to maturity. On an area basis, between 16% - 20% of the stand may be removed while putting in striproads (4m and 5m striproads respectively). But this figure has a lower effect on total volume production for a few different reasons. Striproad width is measured from stem to stem, which is an unrealistic measure because it does not allow for any space between edge trees. A more precise measure of striproad width would account for the crown space of edge trees, reducing the measure of stand area removal.

Edge trees may compensate the area removal with faster volume growth and diameter development (Eriksson, 1987). This is partly explained by the slow release of nutrients from the decomposing slash placed on the striproad, and the greater amount of direct light reaching the crown. The edge tree effect is greatest within the 0 - 3 meters adjacent to striproads, but can be observed up to 4 – 5 meters away (Eriksson, 1987; Mäkinen et al., 2006). In spruce stands, edge trees can exhibit up to 50% diameter growth increases compared to those located furthest away from striproads, in the 5 years after thinning (Eriksson, 1987). The growth rate of edge trees slows to the stand average, the longer the period following the striproad cutting. Overall, when thinning intensity is low to moderate, the volume losses from strip roads is compensated by increased growth in edge trees and improved quality and diameter assortments resulting from the thinning (Spellmann & Schmidt, 2003).

Whenever machines enter the stand, there is the possibility of damage to remaining trees. Edge trees are particularly vulnerable to stem damage when the harvester moves trees from the intact forest area to the striproad where it awaits forwarder pickup. Stem damage results from the skill of the harvester operator, and from the size of trees being removed. Larger trees are harder to control during falling and tend to have larger branches, both increasing risk of damage.

Both harvesters and forwarders can contribute to fine root damage of edge trees, if there is not sufficient slash placed on the striproad to prevent soil compaction and rutting, or if harvesting is conducted during wetter parts of the year. Risk of root damage increases with the combined machine weight (machine plus load) and the number of passes and decreases with increasing slash thickness (Eliasson & Wästerlund, 2007; Sirén, 2000). Eliasson & Wa (2007) suggest 0,2 m of slash is required to adequately reduce root and soil rutting damage.

3.2 Interview Results

Based on the interview results, the key aspect the forest managers stressed was the timeframe for best influencing the development of a stand. Although rotations range from 60 – 100+ years depending on site fertility, the period to best affect stand development spans from planting to the first commercial thinning. The silvicultural practices prescribed by the managers stress the importance of early intervention.

3.2.1 How thinning contributes to the timber supply

The question "how significantly does thinning contribute to the timber supply of your organization?" was asked to all stakeholders. The replies, although not completely comparable due to the difference in the organizations, trend to one thing: thinning volumes are crucial to Swedish forestry.

Skogsstyrelsen, the Swedish Forest Agency, which also compile yearly statistics on all forestry activities, indicates that "more than 400 000 ha are thinned yearly". Clearfellings are carried out on just under 200 000 ha per year. Thinning volumes account for ca. one-third of volumes while clearfelling volumes make up the remaining two-thirds. On an area basis, two-thirds are thinned while one-third are clearfelled.

Södra reports that between 40 000 and 45 000 ha are thinned yearly while 20 000 ha are clearfelled. Södra reports a similar mix of volumes as Skogsstyrelsen, ca. 30% from thinning and 70% from clearfelling.

SveaSkog, the state owned company, reports that for the region of Småland, ca. 10 000 ha are thinned yearly while only 3 000 ha are clearfelled. 40% of volumes come from thinning while 60% come from clearfelling. The reason for the higher percentage of volumes from thinning is because there is proportionally less clearfelling on SveaSkog landholdings.

Leif Olofsson of SydVed, also called "The thinning company", explains that his company has for a long time specialised in thinnings. They are a purchaser of "standing timber rights", typically from family forest owners. This method of sale allows them to benefit from their efficiency in thinning, while providing forest owners with FSC certification and thinning services based on Swedish Forest Agency standards. In this manner, SydVed provides pulpwood to its owners, Stora Enso and Munksjö. Over 95% of its harvest is from thinnings.

3.2.2 Expected volume removals

In average sites growing spruce (G24), volume removed at final harvest is between 200-220m^3, which does not include standing live and dead, as well as dead wood left on the ground, which equals approximately 10% of the harvested volume retained after harvest for nature conservation measures.

The first commercial thinning typically yields between 40-50m^3 and the second thinning yields between 70-80m^3. The assortment mix at the first thinning is almost exclusively pulpwood or energy wood. Up to half of the volume during the second is in the smaller sawlog assortment. Over the length of the rotation, a stands yield approximately half of its volume as pulpwood and the other half as sawlogs. One of the goals of the thinning programme is to remove more pulpwood in smaller diameter classes and to create larger diameter sawlogs at the time of clearfelling. The result of two thinnings throughout the rotation produces a mix of up to 80% high value sawlogs at the final harvest, impossible to achieve without thinning a stand.

3.2.3 Thinning as a response to fibre needs and available supply

Fredrik Klang of SveaSkog explains the modern take on the link between available timber supply and industry development. Looking at the age-class distribution of SveaSkog's forestlands, most of the area comprises young and medium age forests. Only a small proportion of the area is in the clearfelling age class. Industries have adapted to the available supply of timber. There are large quantities of smaller diameter timber and larger timber of low quality that the pulp and paper industry uses. The high quality larger diameter timber is used by the sawmilling industry. The industry has responded to the available supply since the forest can't adapt to industry demands.

3.2.4 Thinning and a positive economy

There was consensus that thinning contributes to a positive economy over the rotation of the stand. The current economy for thinning volume is good, making it an attractive option not only for future development, but also for income in the short-term. SveaSkog reports profits of approximately 100 SEK/m^3 for the first thinning and 200 SEK/m^3 during the second thinning (5 year average, up to 2012) (100 SEK is approximately 16 CAD as of November 2013). However, the first thinning would be done at a cost, seen as an investment, and a silvicultural prerequisite for good forest management. The first thinning is the time in the rotation where you can control the growth and resources of the site on select quality stems, which are crucial to the future income.

3.2.5 Technological advancements: Making use of small timber

There are two pre-requisite for thinning volumes to contribute to the *useful* timber supply. First, there needs to be a market for the wood and secondly there needs to be efficient harvesting technology capable of handling small trees.

Södra has over 200 harvesting crews on contract, but they keep six in-house crews (one harvester and one forwarder makes up a team). The main purpose of in-house teams is to test new technologies and explore potential efficiency gains. Recently, they conducted a study to determine the smallest diameter timber that could be harvested with break-even economics. Using a multi-grip harvester and in a good pulpwood market, 7 cm DBH stems can be harvested without running a loss.

SveaSkog describes a similar method to ensure constant efficiency gains. They also contract out all the harvesting but maintain a research and development programme. When they discover an efficiency gain, they want contractors to adopt the new practice to recover their research investments. To do this, they give contract crews three years to adopt the new technology. Crews who adopt the new technologies early will achieve higher profits. But following the three-year grace period, SveaSkog adjust their price-lists to reflect the potential productivity gains. Contractors who have failed to modernise will no longer be as competitive as those who have.

The interviewees all explain that harvesting technology has adapted to harvesting small timber economically, in response to small timber being the only new source to expand supply. Thus, the milling industry has been the limiting factor in determining the end-use of the product: energy, pulp or sawn goods. Minimum sawlog requirements in specialised sawmills is 10 cm top and 2 m length. Minimum pulpwood requirements is 5cm top and 2m log length. Dr. Bergqvist of Skogsstyrelsen explains that total stand volume is 10-20% higher when volume is accounted until ca. 1cm top. Although it is not likely feasible for sawmills to use such small timber, the pulp industry is working hard to develop debarking technologies to process logs with almost no minimum top diameters, thus again increasing timber supply via improved technology.

3.2.6 Risks associated with thinning?

I raised the issue of risks associated with thinning with the interviewees. There were some concerns with the risks, but the benefits outweigh the costs in this respect.

Concerning storm risk, the greatest danger in wet snow followed by high winds, as is common in much of southern Sweden. In some instances, dense unthinned stands created a blanket capturing much of the snow in the canopy. These were severely damaged compared to thinned stands, which did not intercept as much snow. The literature also reports that thinned stands are also at high risk of windthrow for approximately five years after treatment (Pellikka & Järvenpää, 2003). Their response was that many stands are managed too late. Early cleaning and PCT need to be done to reduce the number of stems while increasing individual stem diameters and H:D ratios. Starting the cleaning when trees are still flexible will reduce the risk of windthrow, but conducting a late PCT in a high density stand where trees are tall and slender will increase the risks regardless of young stand tending. They agreed that "if you start our programme early, and as recommended" you will reduce the risks of storm damage.

Windthrow can certainly pose a risk when thinning at high intensity in older stands. The thinning programmes described by the managers have been revised in the past few years as a response to two major storms affecting Southern Sweden (Per 1999 and Gudrun 2005). The trend is "Go in early and hard", and to start the PCT at a younger age, and to conduct the first thinning when stems are ca. 12 m tall. This should stabilise the stand, individual trees will put on good diameter growth following the thinning and achieve a better H:D ratio. The second thinning should take place when stems are ca. 17-18 m in height. No thinnings should occur in stands over 20 m in height, seen as the limit above which thinning poses significant windthrow risks.

Logging damage is also a risk with thinning. Contractors are allowed 3% damage without penalty, but will be financially responsible for additional damage (Södra). When harvesting the FCT, the strip road has a 4 m width, which is larger than that required at the first thinning, but the appropriate with for the second (or subsequent) thinnings. This is to prevent creating a new edge during the second thinning, since the edge trees will have stabilised since the first thinning when they are smaller and more flexible.

Root and butt rot, by infection of the Heterobasidion fungus is also a concern when thinning spruce stands. Cut stumps are at risk of infection during the warmer periods of the year (5+ C) when the fungus spores are present in the environment. All harvesting activity conducted during warmer periods treat cut stumps with a competing fungus (commercial name: Rotstop®), to prevent Heterobasidion infection.

The managers also discussed the risks of not thinning. Thinning almost eliminates natural mortality (Nilsson et al., 2010), and removes dead trees from the stand during harvesting operations. Managers described the link between thinning and bark beetle management as a significant incentive to thin stands.

3.3 Case study: Thinning opportunities in the Gavin Lake block of the AFRF

A large area of intact forest (2200 ha) was classified by forest condition for the case study. Middle-Aged units were those where commercial thinning was the recommended treatment. Additional to Middle-Aged stands, commercial thinning opportunities were identified in a select number of other units, based on criteria for thinning described in Section 2.3.4 Criteria for thinning – Decision making support tool and Figure 3. A total of 957 ha (22 units, 44% total area) have commercial thinning opportunities as management option (including Middle-Aged stands). The analysis for this project focuses on these 957 ha with thinning opportunities, while the entire classification scheme contributes to the information presented to AFRF managers.

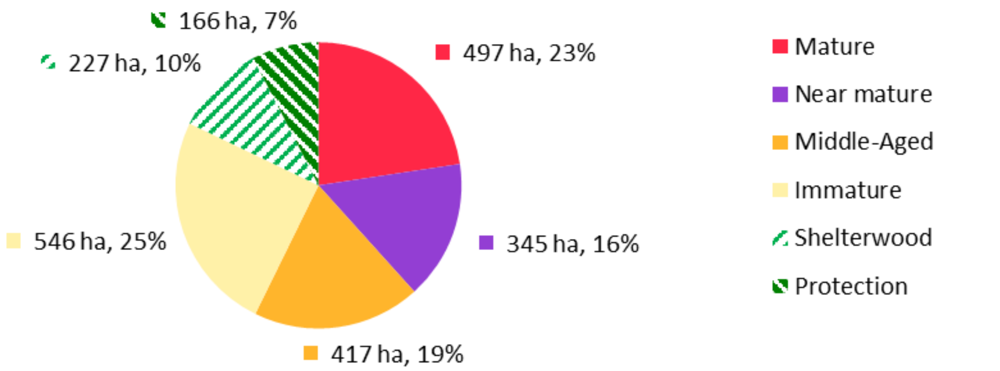


Figure 11 – The subset of the Gavin Lake block which was surveyed for this research, separated by stand classification and maturity level. A total of 2200 ha was surveyed and classified by stand development stage.

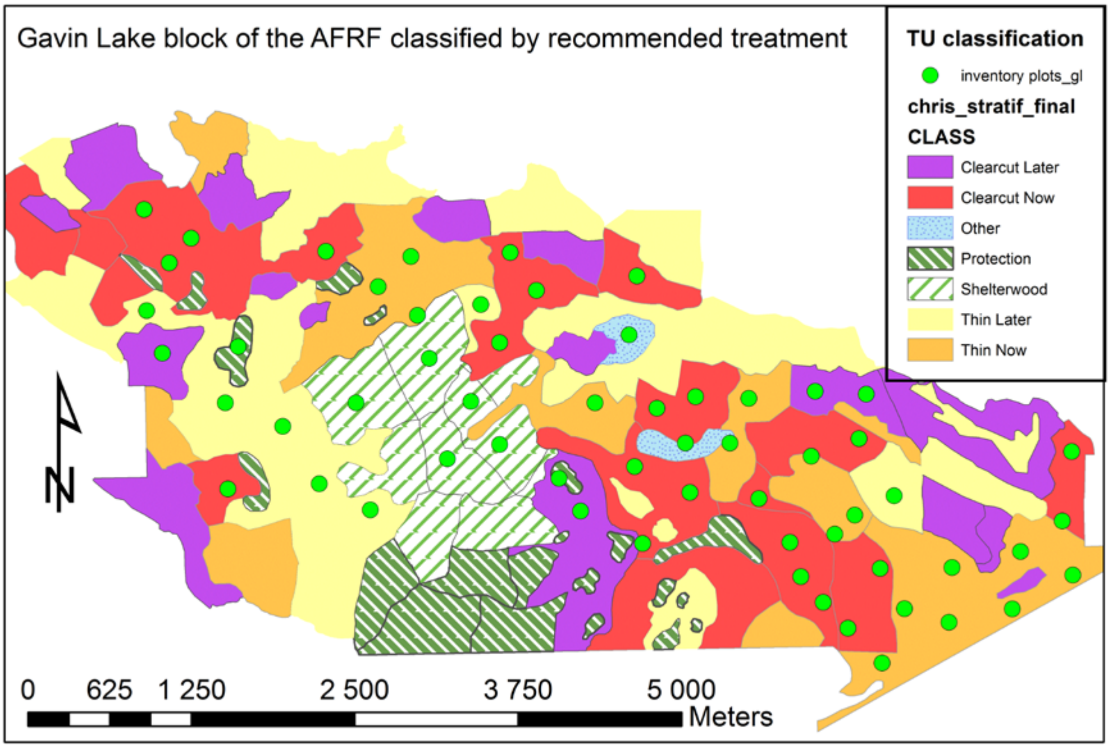


Figure 12 - The Gavin Lake block classified by recommended treatment. A total of 60 cluster plots were used to collect stand inventory information.

3.3.1 A description and comparison of the treatment units with thinning opportunities

A thinning prescription was developed for each unit based on stand condition. In all cases, thinning from below is prescribed. The target BA removal was 40% in Middle-Aged and Immature stands (excluding D15). To minimise storm risk following late thinning in mature stands, Mature and Near-Mature stands have a target BA removal of 35%. The Shelterwood unit is already growing in open conditions, and because of the regeneration objectives for the site it has a target BA removal of 50%. The exception is the Immature unit D15, a salvage stand where capturing standing dead and downed merchantable timber is a primary objective.

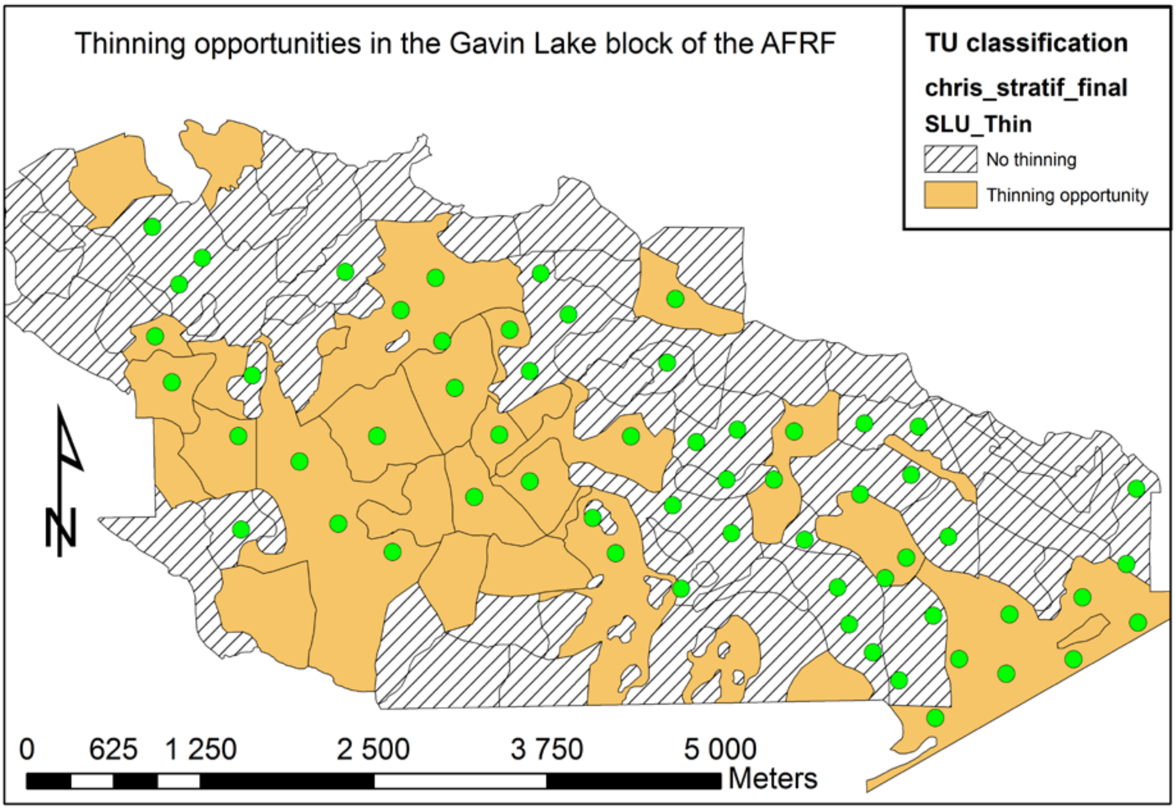


Figure 13 - Thinning opportunities exist in 957 of the 2200 ha classified for the study.

Figure 13 shows all units with thinning opportunities based on the criteria mentioned above. Highlighted units are all Middle-Aged (10 Units, 416,6 18,94% total area) and Shelterwood units (1 Unit, 226,8 ha 10,31% total area), and select units from the Immature (5 Units, 166,0 ha, 7,54 % total area), Near-Mature (5 units, 124,1 ha, 5,64 % total area) and Mature (1 unit, 23,9 ha, 1,09% total area).

Table 6 - Thinning opportunities exist in all Middle-Aged and Shelterwood stands, as well as select units in other classifications, based on the thinning criteria (Figure 3). The table presents all units with thinning opportunities, and provides an estimate of the removals immediately available in a first commercial thinning.

Primary classification	Unit name	Area (ha)	Standing Vol/ha (m3)	Thinning volume (m3/ha)	BA Removal %	Volume Removal %	Total volume from thinning (m3)
Mature stands	**Axx**	**23,9**	**501**	**156**	**35**		**4 191**
	A08	23,9	501	156		31	4 191
Near-mature stands	**Bxx**	**124,1**	**414**	**134**	**35**		**16 589**
	B02	24	485	149		31	3 570
	B07[1]	3,7	398	130		33	475
	B12[1]	64,9	398	130		33	8 434
	B14[1]	3,2	398	130		33	419
	B16[1]	28,4	398	130		33	3 691
Middle-Aged	**Cxx**	**416,6**	**339**	**125**	**40**		**51 525**
	C01	14,8	306	110		36	1 629
	C02	30,1	353	128		36	3 850
	C03[2]	32,2	294	110		37	3 540
	C04[2]	38,6	306	110		36	4 250
	C05[2]	90,4	306	110		36	9 939
	C06[3]	132	371	136		37	17 952
	C07	35,8	336	123		37	4 403
	C08[3]	14,9	371	136		37	2 021
	C09	7,3	425	156		37	1 140
	C10[3]	20,6	371	136		37	2 801
Immature	**Dxx**	**166,0**	**285,1**	**101**	**40**		**17 443**
	D01	9,2	213	79		37	727
	D03[4]	26,4	304	109		36	2 881
	D04	101	295	106		36	10 708
	D15*	10,4	171	102	50*	60*	1 061
	D16[4]	19	304	109		36	2 066
Shelterwood	**Shxx**	**226,8**	**179**	**83**	**50**		**18 828**
	Sh01	226.8	179	83		46	18 828
Total		**957,4**	**343,8**	**120**			**102 458**

[1,2,3,4] Stand inventory information for these treatment units were aggregated to improve the quality of the model

Thinning removals range from ca. 80 m^3/ha in the Shelterwood unit, ca. 100 m^3/ha in Immature units, ca. 120 m^3/ha in Middle-Aged units, to 130 – 150 m^3/ha in Mature and Near-Mature units. Figure 13 presents thinning volumes available for removal at the first commercial thinning in each units and Figure 14 shows volumes per hectare pre-entry, to be retained and removed for individual thinning units.

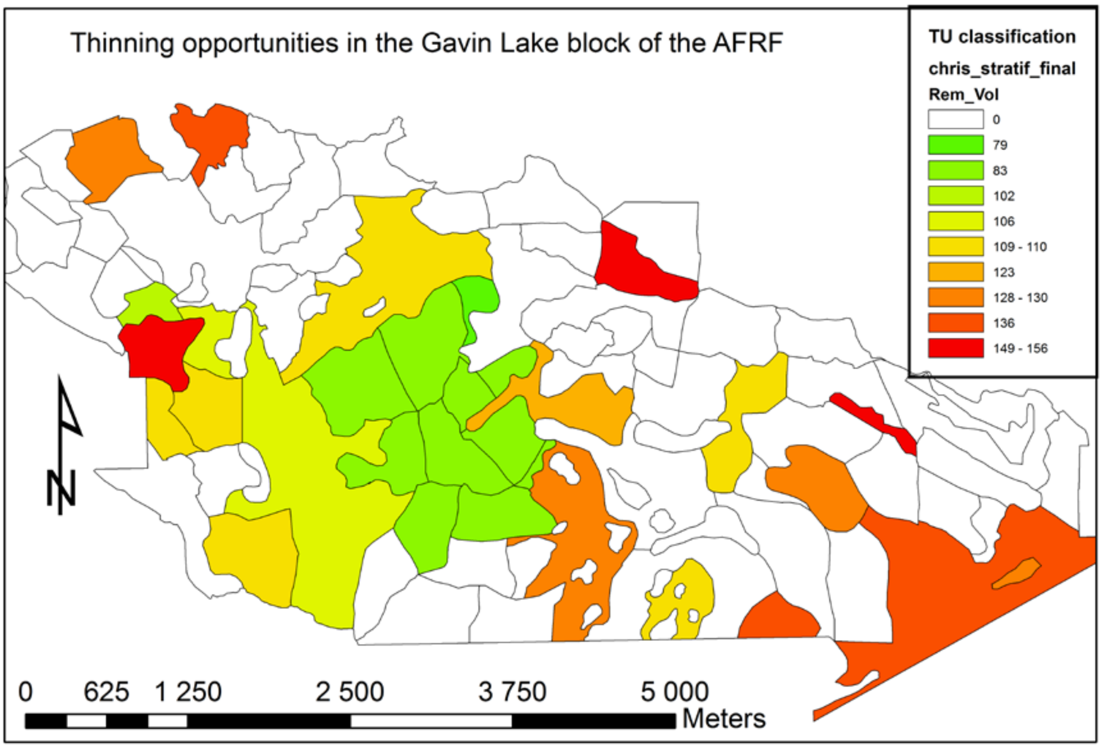


Figure 14 - Volumes currently available for removal in a first commercial thinning from below based on 35 - 50% BA reduction.

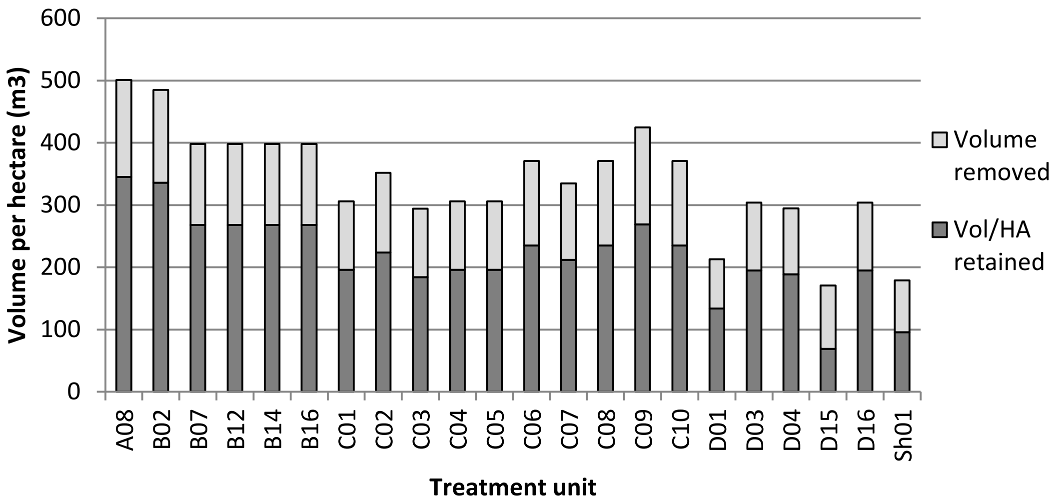


Figure 15 – Volume per hectare of individual units before and after recommended treatments. Minimum threshold for volume/ha removal during a first thinning is 80m^3/ha.

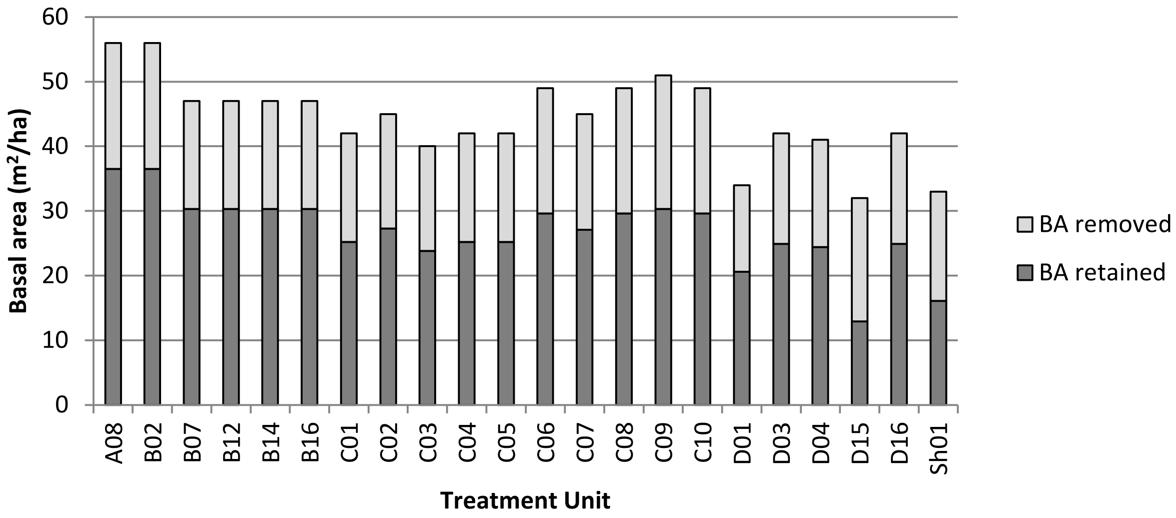


Figure 16 – Current BA, BA to be removed and BA to be retained of TUs with commercial thinning opportunities. Target removal is 35% in A08 and Bxx stands, 40% in Cxx and Dxx stands and 50% in D15 (salvage) and Sh01 TUs.

The recommendation is for a thinning from below for all units. The thinning ratio (average diameter of removed stems/average diameter of stems before removal) is between 0,8-0,85 for most units, D15 and Sh01 have a higher thinning ratio, due to higher thinning grades recommended (Figure 17).

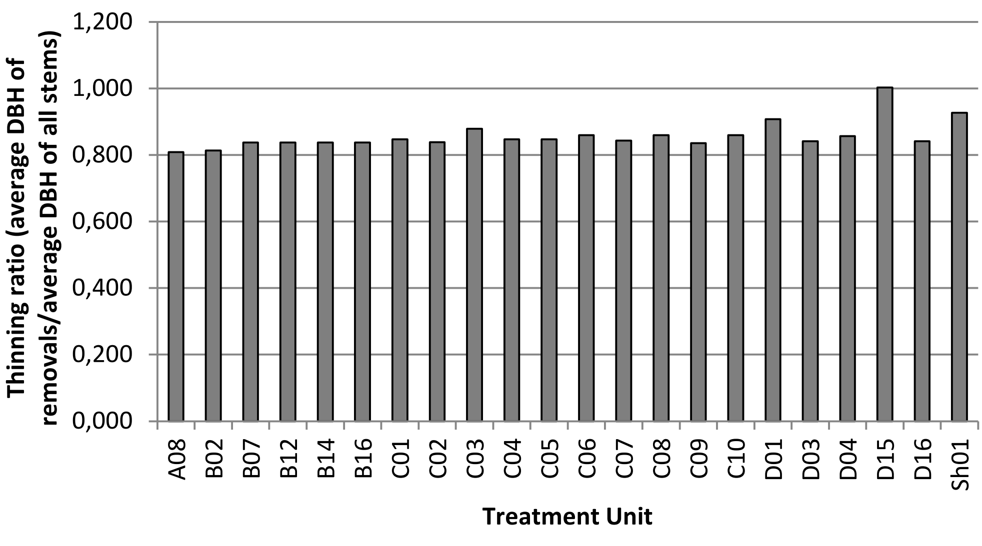


Figure 17 – A thinning ratio below 1 signifies a thinning from below. D15 and Sh01 have higher thinning ratios due to higher thinning grades and more uniform stem sizes.

Regardless of BA and volume removals, residual stands have ca. 400 stems/ha (Figure 18). Following a thinning treatment, natural mortality should not play a significant role and most of the retained stems should reach maturity at the time of the final harvest.

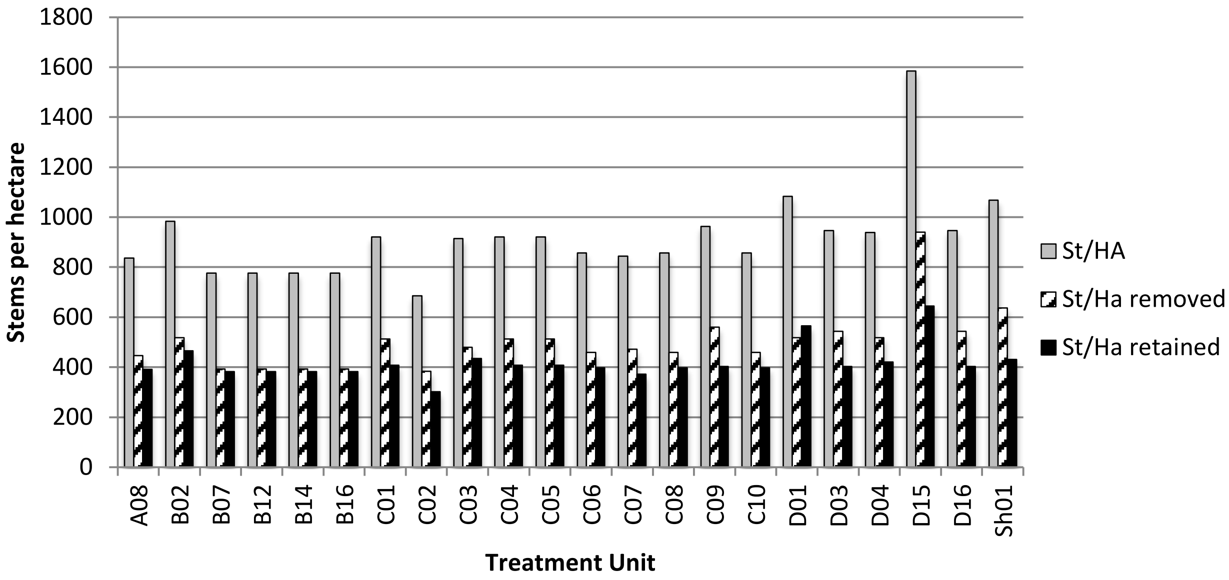


Figure 18 – Current, removed and retained stems per hectare. The goal of the thinning treatment is to focus growth on ca. 400 quality stems per hectare.

Machine productivity and hence logging costs are a function of average tree size of removed trees. Figure 19 shows D*ba* of the average trees pre-entry, to be removed and retained. D*ba* represents the diameter of the "average tree", and is a good indication of logging costs per m^3. Small D*ba* in the D01, D15 and Sh01 indicate high logging costs. In all instances except D15, D*ba* increases after the first entry meaning lower per cubic meter harvesting costs in the future. However, future diameter development in D15 following thinning should translate to lower costs as well.

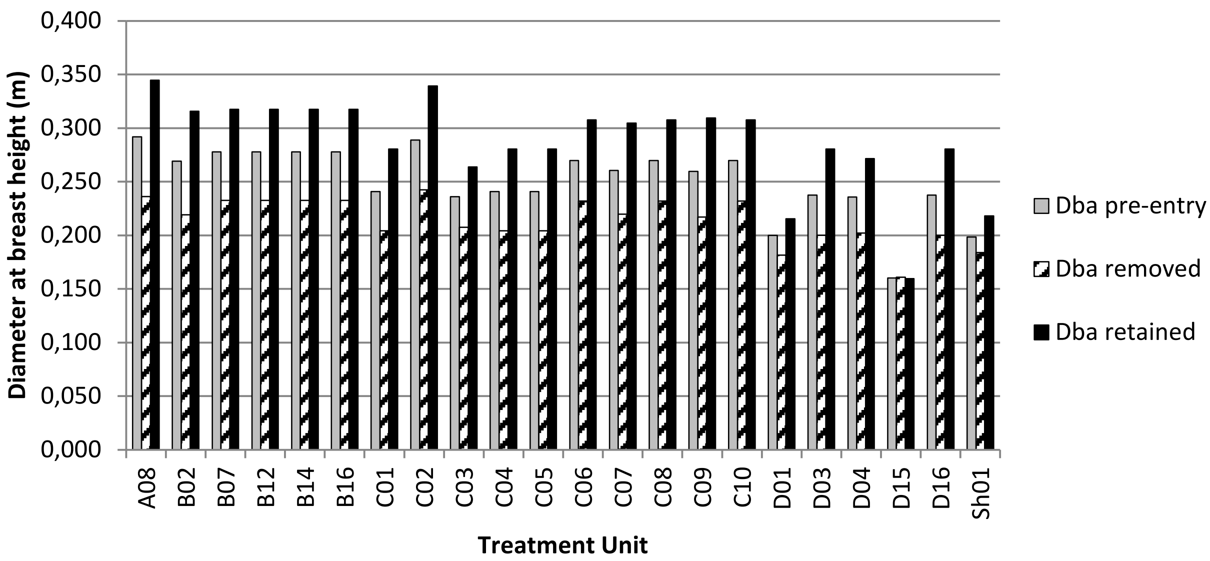


Figure 19 – Quadratic Mean Diameter (D_{ba}) is the DBH weighted by BA and represents the DBH of the "average tree", a good indication of logging costs. Lower values indicates increased per cubic meter logging costs.

Income generated from logging is correlated to removed tree volume. Individual trees with a higher volume are worth more per cubic meter than those with lower volumes (Figure 20). Mature and Near-Mature units have an average 0,3 m^3/tree removed. Due to a late thinning in mature stands, it was important to retain dominant stems to minimize storm risks. Retained stems in these units are proportionally significantly larger than those of the other less mature units. Middle-Aged stands range from 0,2-0,3 m^3 and average about 0,25 m^3/per tree removed, while thinning in Immature stands removes ca. 0,2 m^3/tree, and concentrates growth on significantly higher value stems.

Thinning in D15 and Sh01 might not generate much income during the first thinning. However, the "salvage thinning" in D15 has two objectives, future crop quality and capturing standing dead volume. Thinning in Sh01 also has regeneration goals. The added objectives in these two units might justify break-even cost/revenues or a slight investment in the retained stands.

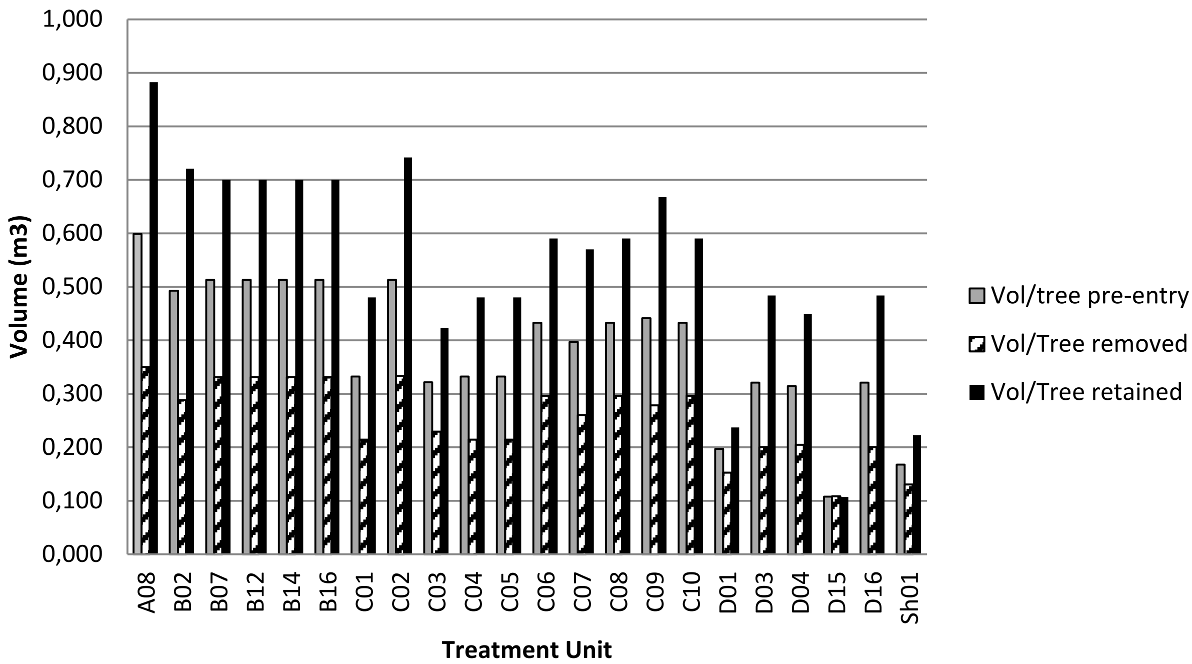


Figure 20 – Average volume of individual trees pre-entry, to be removed and retained. Mature and Near-Mature units have high differentiation between removed and retained to minimize risks. There is less differentiation in the other units

4 Discussion

One of the significant limitations on the application of commercial thinning as a means to mitigate the MTTS shortfall is the current lack of market for small diameter timber. There are 13 pulp mills in Interior BC located in nine cities (British Columbia Forest Service, 2008). Where there is a market for small diameter timber thinning volumes could significantly contribute to the timber supply. However, prohibitive log hauling costs limit the distance or area served by these mills, and pulpwood is treated as waste wood in regions deemed too far from processing facilities. Thus, in remote areas, the main market is for sawlogs, which early thinnings produce very little of. Current minimum sawlog dimensions also pose a limit to thinning volumes contributing to the timber supply. In much of the interior, minimum sawlog dimensions are 3,76 m length and 11,4 cm top. Small diameter logs shorter than the minimum are generally treated as waste, unless specialty buyers can be found. Note that larger diameter logs may have shorter minimum lengths.

Another significant hindrance to investments in incremental silviculture such as thinning is the use of volume-based tenure, which currently accounts for 80% of Crown forest tenures in BC (BC Ministry of Forests Lands and Natural Resource Operations, 2012). Tenure issues and reform are beyond the scope of this thesis. However, the BC government in its recent report by the Special Committee on Timber Supply – aimed at looking for ways to mitigate the MTTS gap – has recommended looking at moving towards more area-based tenures, at least in a precautionary trial approach (Special Committee on Timber Supply, 2012). Adopting this tenure system may accelerate the use of more advanced silvicultural practices, leading to increased thinning with associated gains in timber supply in the mid and long term. West Fraser Mills Inc, an important industry in the Interior, reports 15% increases in AAC by moving from volume-based to area-based tenures, as a result of managing a fixed landbase (Special Committee on Timber Supply, 2012).

Thinning is not currently practiced on a large scale in BC, and its adoption and benefits are likely to only occur incrementally. A site-selection process where factors such as distance to processing facilities and tenure type should be applied. Thinning response is faster and more pronounced on fertile sites (Mäkinen & Isomäki, 2004a, 2004c), and this should figure prominently in the site selection process. Beyond the limitations to the implementation of commercial thinning in BC, thinning itself should have positive effects on the MTTS.

4.1 Thinning and the effects to growth and yield

The light to medium thinning programmes reviewed had little effect on total yield for Norway spruce and only slight reductions in yield for Scots pine. Heavy thinning (60-70% BA removal at first thinning) did slightly reduce total yields in Scots pine, but not in Norway spruce (Figures 4 and 5). If thinning risks reducing total yields, it is still justified in net present value calculations by providing income before the final harvest, by improving the quality of the remaining stems and by affecting diameter growth of the residual stand (BC Ministry of Forests, 1999). Log assortments in Finland and Sweden include premium logs, sawlogs, pulpwood and in many regions energy wood. In much of the Interior of BC, the only assortments are premium logs, sawlogs, and *some* pulpwood (sawmill residue contributes a significant amount of pulp chips). Quality and diameter growth, both improved with thinnings, determine the end-use of the timber. By creating more sawlog grades, thinnings have the potential to greatly influence the merchantable timber supply.

The lower total yield from the heavy thinning compared to the no-treatment option could be made up by shorter rotation, highly influenced by average DBH of trees in the stand. All thinning programmes significantly increased diameter development (Figures 7 and 8). Considering that the BC MTTS will be filled with trees that are currently growing, a heavy early thinning could help shorten the time before these become merchantable.

The influence of thinning on log assortments has beneficial effects on both the MTTS and on a positive economy. Figure 7 shows that with 33% BA removal at first thinning, sawlog volume increase from $110m^3$ to $149m^3$ in Scots pine (27% increase) and from 255 m^3 to $330m^3$ for Norway spruce (29% increase) at final harvest (Mäkinen et al., 2006). Thinning thus produces both higher sawlog volumes and more valuable logs (logs of larger diameter). Regions of BC with a pulp market will benefit from earlier access to pulp volumes, while even regions without a pulp market benefit from the higher sawlog volumes produced from thinned stands.

4.2 Risks of thinning

The risk of windthrow increases immediately after thinnings, and lasts a period of ca. five years after a treatment. Light thinning, and thinnings in younger stands pose less risks than heavy thinning or thinning in stands with high dominant heights. Regions of BC with no small-wood market will be tempted to wait until trees reach larger log dimensions before the first thinning. This could leave a stand fairly vulnerable to windthrow for a number of years if thinning intensity is high. On the other hand, multi-strata forests are common in BC, as is present in some of the stands identified as having thinning opportunities in the Gavin Lake case study. In such stands, thinning is prescribed despite the older age, however it is limited to a light intensity of small and supressed individuals forming the lower canopy. This thinning programme is based on current AFRF management, however the windthrow risks might be unacceptable on certain high exposure sites. It has been suggested that keeping the H:D of residual trees below 0,8 for Douglas fir should mitigate windthrow risks (BC Ministry of Forests, 1999). Certain sites may not be suitable for thinning. Especially in unmanaged stands with a wide range of tree sizes, thinning form should be from below taking care to leave trees having already expressed dominance.

Thinning is generally believed to reduce the risk of snow damage. Thinning opens up the canopy and allow snow to fall to the ground, reducing snow-loading on individual trees. Heavy wet snow followed by periods of extreme wind present significant risk, regardless of thinning programmes.

The risk of infection from the Heterobasidion fungus is a risk in conifer stands in most of the Northern hemisphere, especially when fresh tissue is exposed during the growing season (5+ ºC). In Northern Europe, the fungus has an affinity for Norway spruce, Scots pine being generally perceived as being more resistant. Stands are typically free from infection until the first thinning. As the managers interviewed indicated, all fresh cut stumps exposed during thinnings in Norway spruce are treated with a competing fungus to prevent widespread infections with acceptable results. Stands in BC are not immune to root and butt rot, but there is limited research on which tree species are favoured by Heterobasidion. If thinning in Interior BC becomes widespread, a good understanding of host preference and suitable control measures should be studied.

Machine-caused mechanical damage is possible whenever heavy machinery enters a stand, in the form of damage to residual stems and soil compaction/rutting. Soil damage is minimised when the soil is dry or frozen and placing slash on strip roads helps contain the damage. Smaller loads during primary transport may be required when the load bearing capacity of the soil is low (when soils are wet). Damage to residual stems during the harvesting phase is lower in smaller timber and with increased operator experience. Late thinnings in dense, middle-aged stands with no previous spacing may lead to significant damage. The larger the removed stems, the greater the risk to residual stems.

Bigger machines may be better suited to control trees during falling operations, reducing damage. But the larger machines themselves may be more susceptible to bruise or wound residual stems. In all thinning operations, the selection process should start by eliminating damaged stems, and the remainder of stems removed should contain those damaged during the initial falling.

There might be a significant learning curve for BC operators who are used to the clear-cutting silviculture system. Thinning-specific harvesters are a little smaller than those used during clearcutting, but are not abundant in BC. Using feller-bunchers for thinnings may not be the ideal equipment but may be all that is available. The relationship between profitability and productivity for forest operators make it difficult for inexperienced operators to be competitive, and these may not be willing to risk turning a loss. Some pricing incentive may be required in order to develop the skills required for effective thinnings, considering training and machine configurations.

4.3 The Gavin Lake Case Study

The work conducted for the case study was to assess the forest condition and classify the Gavin Lake block into distinct TUs. The AFRF management team was particularly interested in commercial thinning opportunities. This thesis aims to extend some results from the case study to wider implications for Interior BC. What is clear from the case study is that thinning opportunities do exist in the Gavin Lake block, divided in three categories of stand condition: thinning in mature and near-mature stands (A08 and B TUs), thinning in middle-aged stands (C) and thinning in immature stands (D and Sh stands). The distinction between these three categories is important because of the different effects they have on the timber supply in the mid-term.

Commercial thinning can have different effects on the timber supply:

- Accessing timber from visually sensitive areas
- Accessing timber before the final harvest
- Improve the growth of the residual stand
- Capture volume otherwise lost to natural mortality
- Redistribute harvests over time
- Break up the concentration of forests in similar seral stages (BC Ministry of Forests, 1999)

The research forest in not constrained by significant visual quality objectives (VQO's), and thinning in not thought to increase the amount timber available for such reasons. However, in areas with constraining VQO's, thinning has the potential to greatly increase the area included in the timber harvesting land base. This could have significant beneficial impacts on timber supply, but must be assessed on a case-by-case basis.

In all thinning stand types, thinning provides timber before the final harvest. The greatest effects for the timber supply would be when thinnings are conducted in middle-aged and immature stands. Such stands could not be clear-felled immediately, and thinning volumes directly improve timber supply in the short and mid-term. Thinning in mature and near-mature stands' effect on timber supply are related to managing timber flows, and potentially altering the age-class of the forest.

Thinning responses vary by stand age, being more pronounced in younger stands and less so in older stands. Besides stand level responses, thinning in older stands provides less tree-level benefits, because stem-selection has largely been done and differentiation between crown classes has already occurred. In such stands, thinning must target smaller stems, regardless of the quality or species of the dominant trees, to maintain a fully stocked and windfirm residual stand. Thinning in younger stands, before significant crown differentiation occurs, allows growth resources to be concentrated on select quality stems. This should have positive benefits for the timber supply in the mid-term.

Thinning in all stand types should capture natural mortality thus providing additional volume compared with unthinned stands. Thinning in older stands with differentiated strata specifically targets smaller suppressed trees that may otherwise die and decay before the end of the rotation. Thinning in young and middle-aged stands, before canopy differentiation occurs, should capture volume before trees become suppressed and whose growth would slow or cease due to competition.

Where thinning in older stand types has the greatest effect on timber supply is in the redistribution of harvests over time and in breaking up the concentration of forests of similar seral stages. Thinning in mature stands would increase the length of the rotation compared to unthinned stands. Although this could reduce short-term supply, benefits in the mid-term should be achieved. This could be important for managing timber flows, and creating sufficient seral stages where the increment would more closely match mature volume.

As experience related to thinning grows in the Interior, thinning programmes should adapt and reflect new knowledge. For instance, current practices in the AFRF call for 40% BA removal during thinnings, while I modelled thinnings in mature stands based on 35% BA removal for windthrow risk mitigation. If such precautions turn out to be unnecessary, higher thinning grades could be used. Proven and demonstrated long-term gains in merchantable volume resulting from commercial thinning could be transferred to immediate harvest increases in older stands, should such forest conditions exist.

In the older stands, the thinning provides volumes in the shorter term, captures some of the natural mortality and reduces future logging costs. Individual tree response may be limited, as the canopy already has distinct strata and thinning of old stands should really focus on the smaller trees. The opportune time for stem selection has come and gone, and managers the dominant stems must form the residual stand. Thinning in less mature stands should have significant effects on the residual stands for diameter development and focusing growth on select quality stems, and benefits should be realised in the short to medium term.

4.4 Limitations of the study

There are certain limitations of the analysis of thinning effects on growth and yield in Nordic countries and their applicability to the BC context. Most stands in BC are mixed-species stands, while the information reviewed focused on the response of monocultures to thinning treatments. The stand management history is also very different. While most stands in Nordic countries have a long history of forest management with silvicultural regimes, most of the stands in the Interior either originated from natural processes (eg. Fire) or resulted after selection forestry targeted certain species exclusively. The response of the BC species will likely differ, but the general trends of stand responses after thinnings should be applicable.

The semi-structured interview process conducted aimed more at identifying themes useful to the research and having informal conversation with the interviewees, as opposed to asking every interviewee the exact same questions. One disadvantage to this process is you cannot conduct statistical analysis on the responses. The advantages with a more flexible interview process are that special knowledge and insight into topics overlooked in the questions have the opportunity to come out.-

The case study conducted is site specific to the Gavin Lake block of the AFRF. Limited time and resources, and the pragmatic goal of developing a workable harvest plan for the research forest, means that the plot sampling was not completely random. A classification by forest type was done and the sampling aimed to capture the variability in each type. Stand inventory information was collected according the priority level given to each treatment unit. High priority near-final harvest TUs had more sample plots, while low productivity and remote TUs had less sample plots. There are models available from the literature to calculate heights from diameters (Staudhammer & Lemay, 2000; Temesgen & Gadow, 2004) but some of the model parameters were not readily available from this dataset. Simplified equations were developed from the available data. The AFRF Uneven-Aged Stand Management model was used to analyse the plot data. This model groups diameters by diameter classes starting at 15cm with increments of 5cm. Although these are fairly large classes, the errors are assumed to cancel out. This is the model used by AFRF managers and is sufficient for their management goals.

5 Conclusions

- For Scots pine and Norway spruce, thinning significantly increases the diameter development of residual trees. Similar results are expected in BC.
- For Scots pine, thinning reduces total yield by 0-20% but for Norway spruce, total yield is similar to unthinned stands. Species-specific responses must be evaluated for BC species.
- For Scots pine and Norway spruce, thinning increases the yield of sawlogs, both for size and quality. Similar results are expected in BC.
- By eliminating poorly formed stems, thinning focuses the residual growth on quality stems. Similar results are expected in BC.
- Thinning increases windthrow risk for 0-5 years after the treatment. Thinning in mature stands pose a greater risk than thinning in young stands. Scots pine is more windthrow resilient than Norway spruce. Species-specific responses must be evaluated for BC species.
- Root and butt rot cause significant economic losses in Finland and Sweden. Scots pine is more resilient than Norway spruce to the Heterobasidion fungus. Species-specific responses must be evaluated for BC species.
- Machine-causes losses increase with tree size and decrease with operator experience. BC machine-operators will need training and practice to achieve the quality and productivity of Scandinavian operators.
- All interviewees consider the first thinning to be essential to proper forest management for quality and diameter development. This would be done at a cost, if need be.
- All interviewees consider than thinning increases the net-present value of the stand, by providing income before the final harvest, by accelerating tree diameter development, and by favourably affecting the final assortment of logs.
- The interviewees suggest that a timely PCT and operator efficiency are the two keys to a profitable first thinning.

- Significant thinning opportunities exist in the Gavin Lake block of the Alex Fraser Research Forest
- Thinning in young and immature stands will enhance residual stand quality, diameter development, provides timber volumes before final harvest, and may provide increased sawlog yields.
- Thinning in mature stands may enhance residual stand diameter development, provides timber volumes before final harvest, and delays the time until the final harvest. This helps manage timber flows but does not significantly contribute to the timber supply.

- The AFRF is in a privileged position of having a fixed-area tenure. This is a pre-requisite for, but does not guarantee, investments in silviculture eg. thinning.
- Thinning can increase the mid-term timber supply in the Interior of BC, by providing some volume in the interim, and accelerating the pace at which the residual stands become merchantable for final harvest (based on the diameter of the stems at final harvest).

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Appendix 1

A pictures of a representative stand for each TU prescription

Figure 21 - TU A07 in the Mature stand condition with full stocking of mature trees with a closed canopy.

Figure 22 - TU B12 in the Near-Mature stand condition. Recent blowdown has opened up the canopy, and the stand has been spaced naturally. The residual stand is mature and will quickly utilise freed-up resources.

Figure 23 - TU C03 in the Middle-Aged stand condition. High stocking of merchantable size wood in the smaller diameter classes (15-20 cm DBH) and a closed canopy are representative of Middle-Aged stands TUs.

Figure 24 - TU D01 in the Immature stand condition. The canopy is still quite open, partially due to blowdown. The residual stand is immature. There is good stocking of small diameter stems.

Figure 25 - TU Sh01 in the "Sherlterwood" stand condition, indicative of poor sites that have always grown in open conditions. Stands are fully stocked without full canopy closure due to low site fertility.

Figure 26 - TU Pr02 in the "Protection" stand condition. The water logged stand condition would make harvesting particularly damaging to the soil and make regeneration very complicated.

Appendix 2

GIS tools

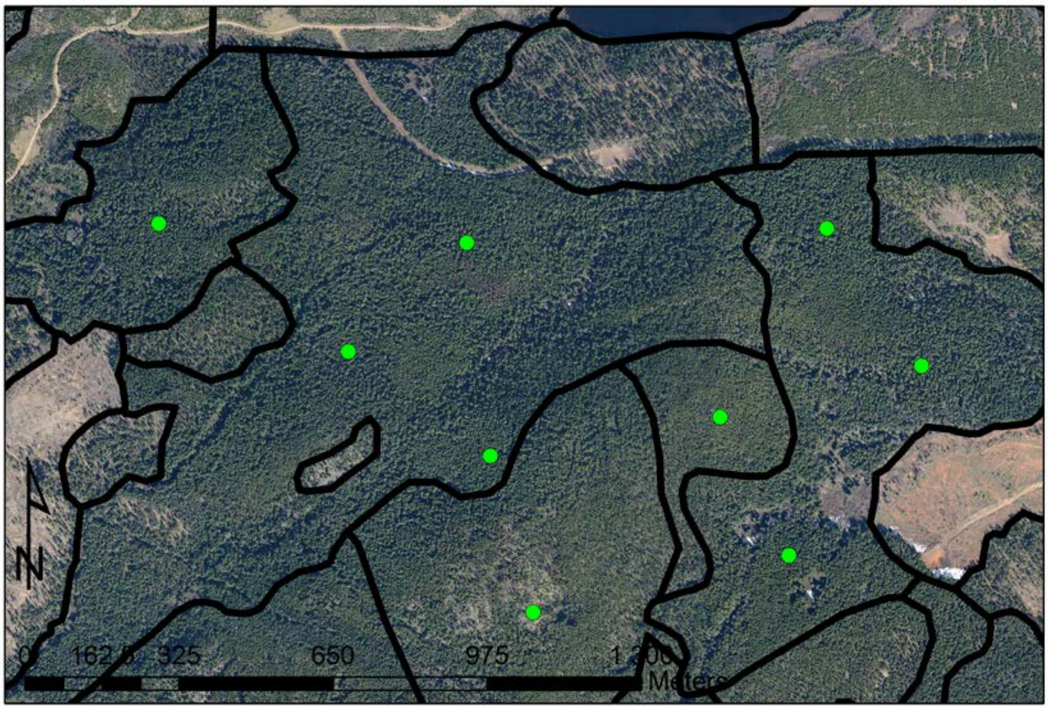

Figure 27 – High resolution orthophoto.

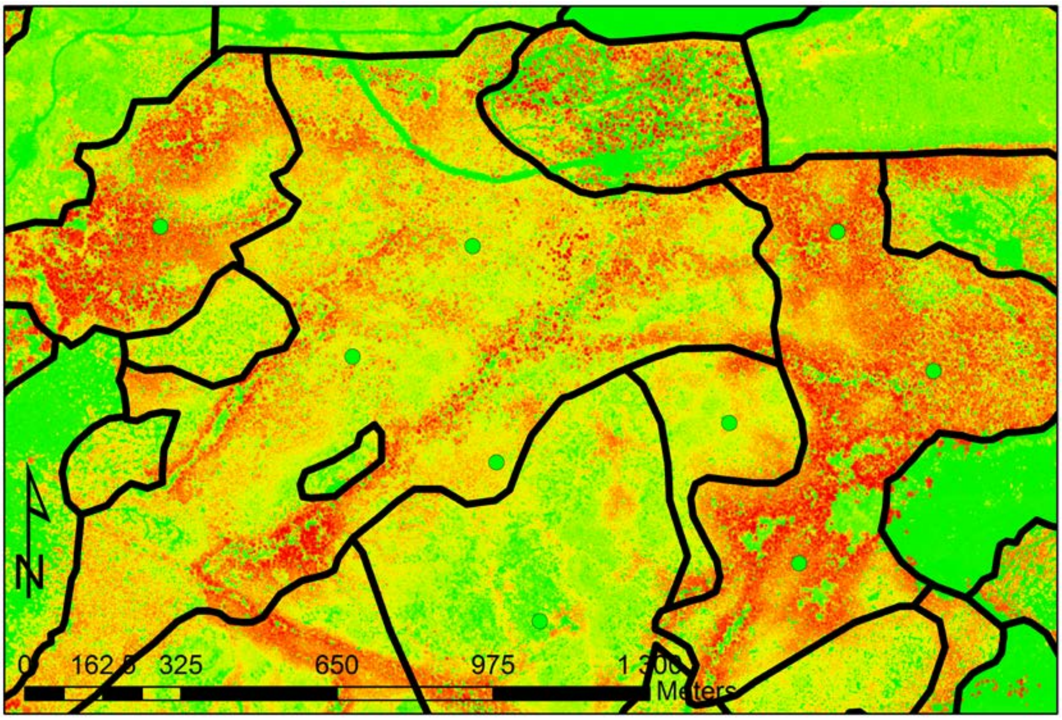

Figure 28 – A map of tree heights made with LIDAR data. The flights collecting the information were conducted in 2008.

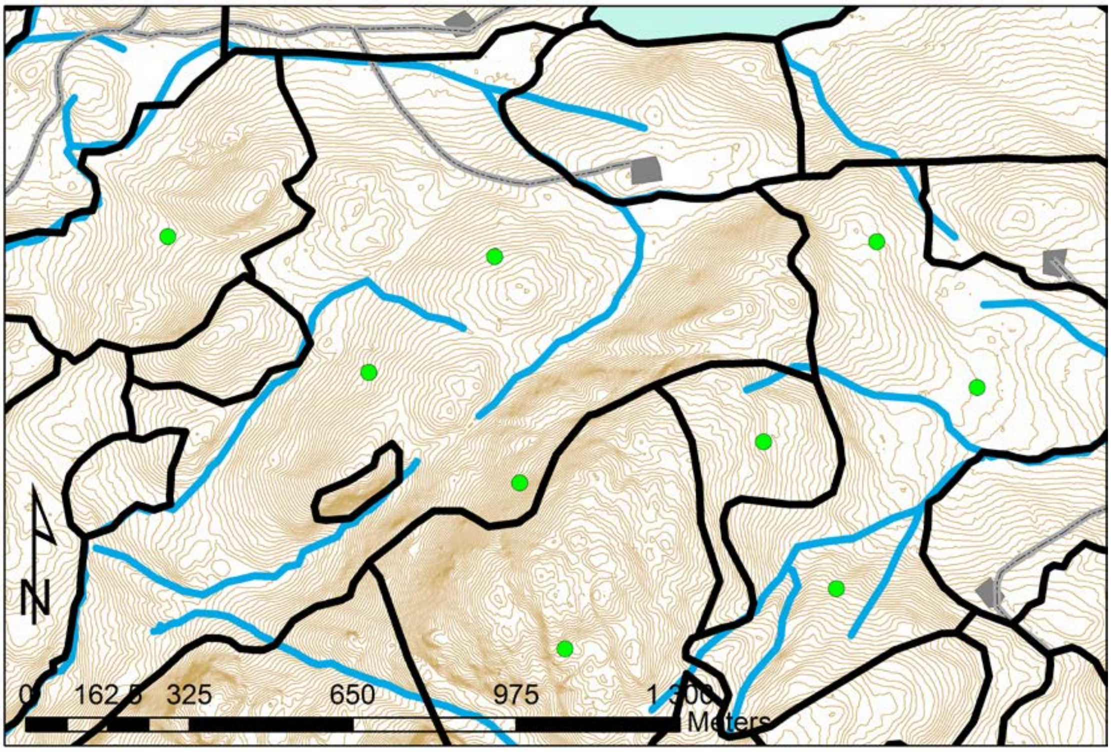

Figure 29 - A 2 meter contour map. The grey lines are existing roads and grey squares are existing landings.

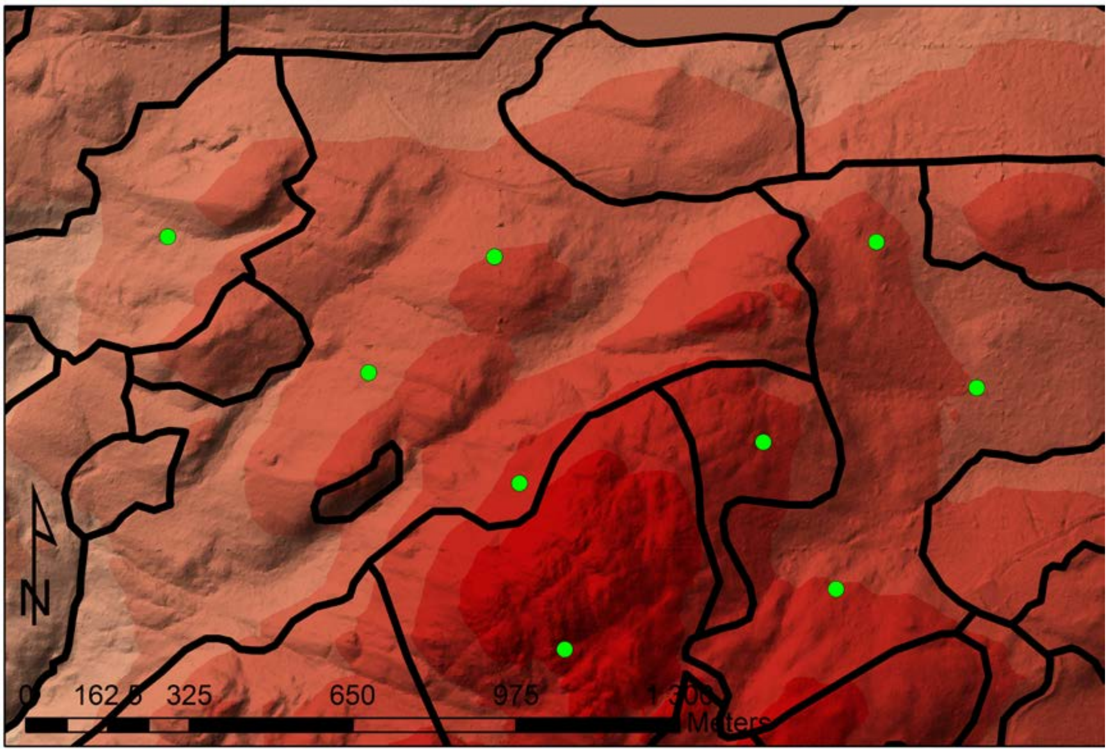

Figure 30 – The Digital Elevation Model gives a visual representation of the topography. Darker colours represent increased elevation. The gradient between light and dark represents slope.