Silvicultural regimes and early biomass thinning in young, dense pine stands

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Abstract

The aim of this work was to determine how early management activities in young, dense pine forests affect tree and stand characteristics and profitability and to assess the future potential for tree biomass harvesting and use. In this respect, the long-term effects of corridor pre-commercial thinning (PCT) and thinning on growth and yield were investigated in 11 Scots pine (*Pinus sylvestris* L.) stands (I). The potential for applying goal-oriented regimes at the PCT-stage was studied in a 20 year old direct seeded lodgepole pine (*Pinus contorta*) stand (II). The influence of management regime on fibre length (III) and profitability (IV) in Scots pine stands was analysed after destructive sampling and using simulations, respectively. The potential of future end-uses of the tree biomass were investigated through a survey and by analysing electricity prices with respect to different tree/wood assortments (V). The form and intensity of PCT influenced the mean diameter at breast height (DBH) and individual tree growth but had little impact on the mean DBH of the largest future crop trees. Stand management regimes with higher stem numbers than conventional options produced substantially larger amounts of stemwood and tree biomass (I, II) and increased the proportion of mature wood in stems that might be suitable for harvest in late silvicultural operations. High intensity early thinning of dense stands limited the proportion of juvenile wood when the stand matured (III). Corridor PCT/thinning did not significantly reduce volume growth or standing volume compared to selective treatments, and may be useful for obtaining biomass from dense stands. Stemwood production was relatively independent of the corridor area, indicating a certain amount of flexibility with respect to harvest intensity in early corridor thinning (I). Boom-corridor thinning at a mean height of 8-9 m instead of conventional PCT generally improved the land expectation value, demonstrating the economic potential of early biomass removal. The economic break-even harvest yield amounted to about 32-44 oven dry tonnes/ha with corridor areas of 40-50% (IV). The value of tree biomass was expected to increase over ten years, especially for raw materials refined into products such as transportation fuels, specialty celluloses, plastics, solid fuels, or chemicals (V). In conclusion, young stand management activities provide forest owners with diverse opportunities to increase biomass yields and uses, manipulate stand and future crop tree characteristics, and increase profitability. New end-uses of tree biomass may influence the profitability of early biomass thinning and the silvicultural regimes of the future.

Keywords: Biomass production, corridor thinning, profitability, fibre length, Scots pine, lodgepole pine

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Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Karlsson, L., Bergsten, U., Ulvcrona, T. & Elfving, B. (2013). Long-term effects on growth and yield of corridor thinning in young *Pinus sylvestris* stands. *Scandinavian Journal of Forest Research* 28(1), 28-37.

II Ulvcrona, K.A., Karlsson, L., Backlund, I. & Bergsten, U. (2013). Comparison of silvicultural regimes of lodgepole pine (*Pinus contorta*) in Sweden 5 years after precommercial thinning. *Silva Fennica* 47(3), id 974.

III Karlsson, L., Mörling, T. & Bergsten, U. (2013). Influence of silvicultural regimes on the volume and proportion of juvenile and mature wood in boreal Scots pine. (Accepted in *Silva Fennica*).

IV Karlsson, L., Nyström, K., Bergström, D. & Bergsten, U. (2013). Profitability and stand development by early biomass thinning applied to dense Scots pine stands. (Manuscript).

V Backlund, I., Karlsson, L., Mattsson, L. & Bergsten, U. (2013). Biorefinery product potentials using tree biomass – Effects of tree assortments and electricity prices. (Submitted manuscript).

The contribution of Lars Karlsson (the respondent) to the papers included in this thesis was as follows:

I The respondent was the main person responsible for data handling, data analysis, interpretations, writing and publishing.

II The respondent was the main person responsible for the planning and performance of the biomass thinning. The respondent participated in measurements, data analyses, and writing the paper.

III The respondent was the main person responsible for field work, fibre measurements, data handling, data analysis, interpretations and writing.

IV The respondent was the main person responsible for study design, data handling, data analysis, interpretations and writing.

V The respondent was the main person responsible for analysis of assortment prices. The respondent participated in planning the questionnaire study and writing the paper.

1 Introduction

1.1 Conventional forest management and thinning

Historically, the key objective for the majority of the forest owners has been sustainable production of wood-based commodities, mainly production of timber, pulp, paper and wood for heating. Thus, focus has fallen on developing practices that increase wood production and quality and on successful stand regeneration. Today, commercial forestry is a long-term commitment, involving management activities during the course of each rotation that strongly influence the growth, density, structure and profitability of the stands. These activities are typically identified and timed to deliver the overall management objectives. The set of management decisions taken over the life-time of a stand are, in this context, referred to as management regimes.

Puettmann et al. (2009) identified so called “core principles” that silviculture has relied on for a long time. In order to ensure predictable outcomes, these principles have resulted in uniform forest stand units in which standard operations can be applied perfunctorily. Between regeneration and final felling, silvicultural regimes typically include various thinning operations. The main aims of these measures are to improve the value-growth of the stand but also to generate an income.

Pre-commercial thinning (PCT) became a standard method in Swedish forestry in the 1950s in order to promote the growth of future crop trees and to reduce damage (Andersson 1975). PCT operations are normally performed between dominant heights of 2 and 5 m and are, therefore, one of the first important tools available to forest owners in order to create a stand that fulfills their overlying objectives. A selective PCT is considered important because it releases future crop trees from competition with broadleaved trees, distributes the remaining value-trees evenly over the land area and creates a uniform stand structure (Pettersson 2001). The timing (dominant height) and intensity (spacing between the remaining trees) of PCT influences both the yield and quality traits of the remaining trees, and thus the first commercial thinning (ibid.). For instance, an early and/or light intensity PCT results in great scope for removal during the first commercial thinning (Huuskonen and Hynynen 2006). Thus, by the way PCT is applied properties such as quality traits, stand growth and structure are influenced.

Once the stand density has been reduced by PCT stands are allocated thinning regimes. Timings and intensities of thinning operations, number of thinnings and the timing of final felling are typically selected on the basis of thinning guidelines (Anon. 1985a, Anon. 1985b). The guidance is normally based on stem number, dominant height, and basal area development (Anon. 1969). Most forest stands are thinned once or several times during a rotation period. Stands on fertile sites are usually thinned repeatedly, while stands on poorer sites (which grow more slowly and generate less biomass) may only be thinned once. Since biomass is removed during thinning, and not all available nutrients are utilized by the remaining trees, the total volume growth is reduced after thinning (Valinger et al. 2000, Mäkinen et al. 2006). For this reason, the volume increment and total standing volume usually decrease with increases in thinning intensity in Scots pine (*Pinus sylvestris* L.) stands (Mäkinen and Isomäki 2004). As crowns and root systems spread following thinning, due to the decreased competition, nutrient utilization becomes more efficient (Valinger et al. 2000). On fertile Swedish sites, such responses normally occur after three or four years, whilst growth enhancement at low-fertility sites occurs after seven or eight years (depending on thinning intensity and timing). This difference is mainly due to differences in the mineralization rate (Pettersson 1996). Further, reducing the stem number means that the trees are less exposed to competition and a mean diameter increase can be expected (Sjolte-Jørgensen 1967, Peltola et al. 2002, Mäkinen and Isomäki 2004).

PCT activity in Swedish forests has decreased in recent decades (Anon. 2012a), since chemical cleaning was prohibited in 1983, subsidies for PCT were scrapped in 1984 and legal obligations to undertake PCT were rescinded in 1994 (Ekelund and Hamilton 2001). Therefore, a large proportion of young forests are currently considered to be overstocked (Anon. 2012b) and not compatible with conventional thinning regimes (Anon. 1985a, Anon. 1985b). Importantly, this forest type needs to be managed in cost-effective ways that are suited to its general characteristics and values.

1.2 Biomass production, stand structure, natural mortality and wood properties in dense stands

1.2.1 Biomass production in dense conifer stands

Tree growth depends on acquisition, efficient use and partitioning of light, water and nutrients. Only a certain proportion of the photosynthate is used to produce wood, the rest is directed to foliage, roots and storage. The allocation, which is crucial for wood yields, can be influenced by genetic selection and silvicultural actions (Canell 1989). As intra-stand competition increases, trees will allocate more assimilates to the stem than to the branches (Nilsson and Albrektsson 1993). Before canopy closure, an increasing proportion of the total production is directed to wood production as stand height increases (Canell 1989). In dense stands, canopy closure will occur at an earlier stage than in widely spaced stands (Zeide 1987) and this also increases the trees' ability to intercept light efficiently (Canell 1989). Thus, stands with high stem numbers typically produce large amounts of stemwood and tree-biomass and display high growth rates (Harms and Langdon 1976, Nilsson and Albrektsson 1993, Pettersson 1993). However, after crown closure, between-tree shading becomes an additional growth-limiting factor (Will et al. 2001).

In theory (if no other growth limiting factors exist), the amount of biomass produced by a tree depends on the amount of radiation intercepted, efficiency of carbon fixation and internal allocation of resources (Stenberg et al. 1994). Several studies have shown that biomass growth exhibits a positive linear relationship with the amount of intercepted solar radiation (Monteith 1977, Vose and Allen 1988, Will et al. 2001, Bergh et al. 2005). In terms of the amount of radiation intercepted, tree development depends largely on the shape and structure of the crown. In general, the role of crown shape and the photosynthetic capacity are affected by stand parameters (site quality and stand density; Stenberg et al. 1994, Will et al 2001). Because it takes a long time to build up a large photosynthetic area with needles and because needled shoots have low photosynthetic rates relative the total amount of foliage, conifer trees initially display low rates of photosynthesis and low growth rates (Canell 1989). However, after crown closure, conifers typically develop canopies that support high rates of photosynthesis (ibid.). At various stand densities, conifer trees seem able to modify their leaf morphology in order to intercept light more efficiently (Will et al. 2001). Needles grown in shaded conditions appear to adapt to the situation by developing a light adsorbing surface area that is large relative to their weight (McLaughlin and Madgwick 1968). According to

Stenberg et al. (1994) a narrow crown shape may promote efficient stem wood production relative to the amount of foliage.

1.2.2 Individual tree growth and stand structure

Although overall growth rates are high in dense stands, individual growth is typically lower and more variable than in conventionally stocked stands (Weiner and Thomas 1986). Regardless of density, in most forest stands the individual growth rate is highly correlated with the relative tree size and below a certain relative tree size, growth rates become small (West and Borough 1983). According to Westoby (1984), the smallest 50-70% of a stand has much the same growth rate, which individually can be considered to be negligible. Therefore stands typically consist of “dominant” and “suppressed” trees, even though the boundary between the tree groups is not static because trees might move into the latter group (West and Borough 1983). Thus, the difference in size between individuals becomes relatively large within a stand. The denser stands are, the earlier they seem to form a multi-storied canopy (ibid.).

1.2.3 Competition and mortality

The relation between the number of stems per given unit of area and stand diameter/average stem weight is considered to determine the ceiling at which further increases in stem size result in a decrease in number of stems (Reineke 1933, Yoda et al. 1963). Therefore, at some point in time, productivity in dense stands typically reaches a plateau or declines. At low leaf areas there will still be little competition for light and trees can continue to photosynthesize efficiently. However, in those cases only a small fraction of the leaf area will contribute and the total production may still be less than in dense stands, even if individual trees are growing more rapidly (Waring 1983). In silviculture, optimal stand densities are traditionally expressed in terms of basal area and number of stems, but could also be expressed as “maximum sustainable leaf area” (Vose and Allen 1988). Before light becomes limiting, trees are able to acquire resources in relation to their size. After canopy closure, the dominant trees still receive sufficient amounts of light whereas small trees experience insufficient light penetration to be able to survive (Weiner and Thomas 1986). Natural mortality therefore becomes evident primarily amongst the smallest trees in a stand (Ford 1975, Weiner and Thomas 1986). Westoby (1984) concluded that mortality typically occurs amongst the smallest 20-30% of individuals in the stand. Therefore, differences in tree size within stands decrease once natural mortality begins to occur (Weiner and Thomas 1986).

1.2.4 Wood characteristics

The characteristics of wood are dependent on genetic material, site quality and silvicultural decisions and they need to be properly matched in order to fulfill the requirements of the end-users and to use the resource efficiently (Downes et al. 2009). Available nutrients, moisture, light and temperature affect wood formation. Early wide spacing and/or thinning to a low stand density will allow the roots and crowns of the remaining trees to utilize the site resources more efficiently. Thus, tree crowns can become larger and more vigorous than when there is competition. Several wood characteristics can be expected to be influenced by stand density. For instance, both compression wood (Cown 1974) and stem taper (Persson 1977) are positively correlated with growing space. Trees standing in solitary allocate resources to their crowns and branches on the lower part of their stem. Studies have shown that the diameter of low branches increases with increases in intensity of PCT (Salminen and Varmola 1993, Fahlvik et al. 2005) and with tree size (Johansson 1992, Pfister 2009).

Silvicultural operations that affect the amount of light available for tree crowns may also increase the amount of earlywood (Denne and Dodd 1981). Generally, small slow-growing trees contain a smaller proportion of earlywood (Mäkinen et al. 2002). In earlywood, cell walls are often thin and lumens are large. Thus, the cell wall fraction per unit wood volume is low; this affects the overall wood density (Zobel and van Buijtenen 1989). The strength of wood generally increases with wood density (Dinwoodie 2000). In *Pinus radiata*, the wood stiffness, i.e. the modulus of elasticity (MOE), has been found to be highly correlated to stand density: values for dense stands have exceeded stands with low stem numbers by 37% (Lasserre et al. 2008). Amarasekara and Denne (2002) also found that ring width, percentage latewood and modulus of rupture (MOR) of Corsican pine (*Pinus nigra* var. *martima*) were correlated with the amount of needle dry weight. In Scots pine, a negative correlation between diameter growth and MOR/MOE has been reported by Høibø and Vestøl (2010). In general, low light penetration and water deficit will reduce the amount of latewood. However, increasing the crown efficiency (e.g. by thinning) of suppressed trees has been reported to delay cambial dormancy, and thereby also to increase the amount of latewood in the annual rings (Denne and Dodd 1981).

Fibre length depends on the rate at which the cambium divides. A high radial growth rate has been associated with a high rate of anticlinal divisions (Bannan 1967). In addition, fibres produced in latewood are typically longer than those produced in earlywood (Panshin and de Zeeuw 1980). Fibre length has also been found to decrease with operations that increase radial growth by reducing the stand density (Cown 1974, Jaakkola et al. 2005). Molteberg and Høibø (2006) found that dominant Norway spruce (*Picea abies*) trees produced slightly shorter fibres than suppressed trees. Fibre development is also affected by the tree crown because fibres formed close to the active crown are typically influenced by growth regulators and hormones and they, therefore, tend to be very short (Briggs and Smith 1986).

Several mechanical and anatomical wood properties display obvious trends with age. MOR, MOE, specific gravity and fibre length all increase with age, whilst micro fibril angle (Mfa) and ring width decrease until a more or less stable level of preferred wood properties is reached (Bendtsen and Senft 1986). Thus, the innermost (juvenile) wood in a tree differs from the outermost (mature) wood in terms of wood properties and quality gradually improves with age. Because the transition from juvenile wood (JW) to mature wood (MW) occurs gradually, there is no distinct boundary between the two wood types. Instead a third wood zone can be defined, namely transition wood (TW; Boutelje 1968, Briggs and Smith 1986). The length of the juvenile period might vary between tree species (Yang 1994) and geographical location (Clark and Saucier 1989) but is generally said to include the first 5 to 25 annual rings. Several authors have reported that the initial stand stem density does not influence the age at which the transition between JW and MW occurs (Clark and Saucier 1989, Yang 1994, Alteyrac et al. 2006). However, according to Kucera (1994) and Eriksson et al. (2006), growing conditions seem to regulate the transition: they found that trees initially growing in extremely sparse stands tended to form MW later than trees in stands with traditional densities. Lindström et al. (1998) found that Mfa was not only affected by age but also by growing conditions. They therefore suggested that juvenile individual tree growth should be suppressed in order to minimize wood with high Mfa. Thus, in order to control the proportion of JW, low growth rates within the JW zone and/or high growth rates in the MW zone are desirable. Therefore, the wood properties of a tree are not only affected by growth rate, they are also dependent on growth rates at different phases in the life-cycle of the tree.

In forestry, the term “wood quality” is, in general, defined by the preferences of the end-users of the wood; predominantly, these users have been the pulp, paper, sawmill and bioenergy industries. Traditionally, pulp and timber price levels have largely affected profitability and have thus exerted control over what were considered to be appropriate silvicultural actions.

1.3 Profitability of management alternatives

Management decisions are based on multiple criteria, of which economic profitability often tends to be the most important. In economic evaluations, taxes, interest rate, the land expectation value (*LEV*), revenues and costs of regeneration, PCT, thinning and final harvest are considered (Pearse 1990). The interest rate, which is usually in the range 2-5% in forestry, strongly influences the profitability of various management regimes. To be profitable, harvests carried out far in the future must generate higher marginal net returns than harvests early in the rotation period, due to the discounting factor. Therefore, the harvest with the greatest net value is normally discounted last. Generally, the intensity and timing of thinning operations have less effect on the present value than timing of the final harvest, and, therefore, thinning guidelines are often relied upon (Klemperer 1996). In order to estimate whether a specific management system is profitable, all revenues and costs must be treated with the same denominator and related to the same point in time. Thus, profitability is usually calculated as the net present value (*NPV*), i.e. the difference between the discounted sum of all revenues and the discounted sum of all costs during the rotation period (Pearse 1990):

$$NPV_a = \sum_{t=a}^{T} \left(\frac{R(t) - C(t)}{(1+r)^{t-a}} \right) \times (1 - tax) + LEV \times (1+r)^{-(T-a)}$$

where NPV_a is the stands net present value at stand age *a*, *T* is rotation, *R(t)* is the revenue of any forest measure at time *t*, *C(t)* is the cost of any forest measure at time *t*, *r* is the interest rate and *tax* is the average income tax. A positive *NPV* indicates that the investment is profitable, while a negative value indicates the opposite. The present value can also be used to rank the profitability of possible management alternatives. If stand age is zero, then there are no trees and the land is assumed to be bare. The net present value then equals the land expectation value, that is $NPV_0 = LEV$. The economic optimum or optimal rotation length can be found by maximizing *LEV*, which is commonly calculated according to the formula proposed by Faustmann (1849):

$$LEV = \frac{\sum_{t=1}^{T} (R(t) - C(t)) \times (1+r)^{T-t} - C_{reg} \times (1+r)^{T}}{(1+r)^{T} - 1} \times (1 - tax)$$

where C_{reg} is the present value of all regeneration cost at year 0.

The final outcome of a management decision based on *NPV* or *LEV* depends greatly on revenues and costs associated with the harvest operations included. The revenues depend in turn on interest rate, assortment prices, timing of harvest, and harvest quantities (i.e. stand growth/standing volume and harvest intensity), whereas the harvest costs depend on stand characteristics and available harvest systems and techniques. However, to use *NPV* and/or *LEV* as a decision tool requires several theoretical assumptions. First, that the capital market is perfect, with a known future interest rate. Second, that future stumpage prices are known. Third, that forest land can be bought and sold in a free, perfect market, in which no individual actor can influence the market price. Fourth, that volume growth and the ways in which quality parameters will change over time are known.

Hartman (1976) presented a modified version of the Faustmann formula that takes non-market priced, public values into account. Boman et al. (2010) defined the multifunctional value of a Nordic forest stand as the sum of the values derived from timber production, recreation, berry picking, game meat, carbon sequestration, biodiversity and water supply. The absolute value of each amenity in a forest stand fluctuates over a rotation period (Boman et al. 2010). For example, if the rotation time is extended, more dead wood is likely to accumulate, which favours biodiversity. Since this variable was taken into account by Hartman, the optimal rotation length is longer than that obtained using the Faustmann formula. All amenities suggested by Boman et al. (2010) are affected, to varying degrees, by tree species composition and stand age. Thus, timber production strongly influences the value of all other amenities and it is difficult to manage the forest in order to optimize all specific values.

1.4 Future of biomass production, demand and end-use

The European Union has agreed upon their 20-20-20 targets; these included the reduction of greenhouse gas emissions by 20%, increasing the proportion of renewable energy to 20% and increasing the energy efficiency to save 20% of the energy consumption by 2020 (Anon. 2009). In order to increase the amount of renewable energy, the Swedish government has formalized its demands on the forest industry for the delivery of tree biomass by publishing national goals (Anon. 2008a). Currently, most of the biofuels derived from Swedish forests originates from the residues (branches and tops) created during conventional harvesting operations. The unused potential in this system is relatively small, amounting to 12 TWh (Lundmark 2006). However, there is substantial energy potential in young, dense forest stands, from which the possible yearly harvest level amounts to ca 23 TWh (Nordfjell et al. 2008).

Although dense stands contain large amounts of tree-biomass, have high growth rates and seemingly produce wood suitable for several end-uses, they are considered less suitable for conventional management, mainly due to the wide range of species and large diameter distribution. Importantly, these stand need to be thinned in order to avoid high rates of mortality (Andersson 1975) and damage mainly caused by snow (Päätalo 2000) and whipping caused by birches (*Betula pubescens* and *B. pendula;* Karlsson et al. 2002).

Applying PCT at a late stage would be expensive because the cost of PCT increases with stem number and tree size (Ligné 2004). Since the trees are too small and the potential pulpwood yield represents only a small fraction of the total amount of biomass, a first pulpwood thinning using conventional mechanical systems would also be costly to undertake. The harvesting costs of mechanical systems used in conventional thinning and final felling operations are mainly influenced by stand parameters including average tree size, number of stems per hectare and forwarding distance (Brunberg 1997, Brunberg 2004, Brunberg 2007). Therefore, such systems become expensive to apply in dense stands where the average tree size is typically relatively small. Instead, in order to exploit these stands, special harvesting systems are required. Time can be saved, and efficiency increased, if accumulated felling heads (AFHs) are used when harvesting young stands. If schematic harvesting (i.e. harvesting in lines, rows, corridors or strips) is practiced, the number of crane movements can be reduced, compared to selective harvest, because the felling head only has to be positioned once (Johansson and Gullberg 2002). In field experiments and simulations, Bergström et al. (2007) found that harvesting in "boom-corridors" ca 1 m wide and ca 10 m long (equivalent to the crane reach), positioned almost perpendicular to the strip roads, improved the harvest productivity compared to selective thinning in young Scots pine stands. The difference in productivity was even more apparent when the size of the harvested trees decreased; thus, the method may be appropriate for stands containing a significant number of small trees. However, further knowledge about the development of the remaining stand and its general characteristics are needed before large-scale application.

Today, forest biomass is seen as a possible raw material for new bio-based functions, including materials and chemicals (Amidon and Liu 2009) as well as solid, liquid and gaseous biofuels (Arshadi and Sellstedt 2008). Therefore, the future value of forest biomass could be influenced by the emergence of biorefineries in which various wood components could be processed into a wide range of end-products (Söderholm and Lundmark 2009). For instance, hemicellulose can be used in the production of liquid biofuels (Mao et al. 2008), biodegradable plastics (Philips et al. 2007), barriers, pharmaceutical hydrogels, constituents of paper beverage containers and aluminum substituents (Backlund and Axegård 2006). Lignin can, *inter alia*, be exploited as a source of phenols, biofuels, a substitute for structural steel and to produce carbon fibres, which can be mixed with commercial polymers and used in several products (Söderholm and Lundmark 2009). Substances found in fractions such as branches, needles, cones and bark are receiving increasing attention for use as feedstock for the production of fuels and high value chemicals (Demirbas 2011).

In long-term forestry rotations, supply and demand are difficult to predict due to the time horizon. For every management strategy, the demands and commercial preferences (i.e. assortment prices and quality bonuses) of society will greatly influence the outcome. In the future, whole-tree biomass may become increasingly important as an assortment alongside pulp and timber. These requirements could potentially be met by exploiting the large amounts of biomass that are produced in young forests with high stem numbers. Adaptive management and silvicultural strategies might therefore require the development of new decision support tools.

2 Objectives

The overall objective of this work was to determine how early management activities in young, dense pine forests affect tree and stand characteristics and profitability and to assess the future potential for tree biomass harvesting and use. Special emphasis was placed on a management regime in which a first biomass thinning (FBT) is schematically applied in young, dense pine stands. The work provides general information about appropriate considerations concerning biomass thinning operations in young, dense pine forests. Specific goals were:

1. to compare the long-term effects of corridor and selective harvest methods in young stands on growth and yield parameters (I)
2. to compare young stand development of different silvicultural regimes in seeded lodgepole pine five years after PCT (II)
3. to quantify and compare wood volumes of different fibre length classes and proportions of juvenile and mature wood within the stem of trees in different management regimes (III)
4. to investigate the profitability of management regimes that combine early biomass thinning with conventional production of pulp and timber (IV)
5. to compare the economic effects of replacing PCT with an early schematic biomass thinning (IV)
6. to investigate how the timing of a schematic biomass thinning affects the profitability of subsequent silvicultural operations (IV)
7. to estimate the potential of biorefinery products from forest biomass and to examine the relationship between the prices of existing assortments (V)

3 Materials & Methods

The material used originated from naturally regenerated (I, III, IV), planted Scots pine (I, III) and seeded lodgepole pine (II). In total 22 experimental sites with site index (SI; Hägglund 1974) varying between 16 and 28 were used for the purpose of this study (Table 1).

Table 1. *Overview of the experimental sites used in the different studies and general stand characteristics*

Study	Treatment(s) studied	Main variable studied	No. of sites	Range of latitude N	Range of altitude (m.a.s.l.)	Range of Site Index (m)
I	Corridor PCT	Growth and yield	2	62-65	20-175	16-23
I	Corridor thinning	Growth and yield	9	56-66	175-415	22-27
II	PCT of varying intensity/corridor thinning	Growth and yield	1	64	310-340	20
III	No thinning/ thinning to 300 stems/ha	Fibre length	1	64	210	23
III	No PCT + late thinning	Fibre length	1	64	260	22
III	Late PCT to 600 stems/ha	Fibre length	1	64	240	21
III	3 m spacing	Fibre length	1	64	330	23
III	10 m spacing	Fibre length	1	64	195	19
V	Schematic biomass thinning (simulation)	Profitability	5	58-61	40-180	21-28

3.1 Paper I

Data from two experimental field-trial series were used to evaluate the long-term effects on growth and yield of corridor harvesting performed at the PCT- (dominant height = 5 m) and first thinning stages (dominant height = ca 9 m). The data on the effects of the thinning treatments in PCT stands were collected from two experimental sites laid out by the Swedish University of Agricultural Sciences during the early 1970s. The two sites, hereafter referred to as the IntSI (Intermediate SI) and LowSI sites, each consisted of two blocks. Treatments compared in this study were:

1. Selective PCT to 1400 stems per hectare (S1400)
2. Selective PCT to 1000 stems per hectare (S1000)
3. Corridor PCT, with 57% corridor area (Cor57)
   - total cleaning of 2 m wide, parallel strips leaving 1.5 m wide untouched strips
4. Corridor PCT, with 65% corridor area (Cor65)
   - total cleaning of 2.8 m wide, parallel strips leaving 1.5 m wide untouched strips
5. Corridor PCT, with 73% corridor area (Cor73)
   - total cleaning of 2 m wide, parallel strips leaving 0.75 m wide untouched strips
6. Corridor PCT, with 79% corridor area (Cor79)
   - total cleaning of 2.8 m wide parallel strips leaving 0.75 m wide untouched strips
7. Corridor PCT, with 82% corridor area (Cor82)
   - cleaning as in (3) complemented with similar cleaning at right angles, leaving squares with 1.5 m sides untouched

At the IntSI site, the PCT treatments were applied at a stand age of 14 years, when average stem densities varied between 10400 and 14400 stems ha^{-1} and the last assessment was carried out in 1999. At the LowSI site, the treatments were applied at a stand age of 25 years, when average stem densities were 9600-11100 stems ha^{-1} and the last assessment was carried out in 2001. In each of the corridor treatments, corridors were marked in advance and natural gaps in the stands were used to minimize the area of bare land (Pettersson 1986). For every treatment except the C treatment, future crop trees amounting to 1400 stems ha^{-1} were marked and numbered, enabling increments of individual trees to be monitored during subsequent assessments. Every treatment unit was surrounded by a 5 m wide buffer zone which was treated in a similar way as the core plot.

Data on the effects of thinning treatments in first thinning stands originated from a regeneration trial established during the period 1951–1960, which was converted in 1974–1981 into a thinning experiment encompassing 14 pine sites and five spruce sites located throughout Sweden. For the purposes of this study, nine pine sites that not had been subjected to thinning since establishment and were last measured after 1996 were used. For this conversion, plots where initial treatments had been originally applied in a row design with 30 seedlings per row (1.5 × 1.5 m spacing) were each divided into two subplots, in which the following two thinning treatments were applied:

1. 50% Corridor thinning (two rows removed, two rows left)
2. 50% Selective thinning of basal area (performed as thinning from below)

Dominant tree heights were estimated by Näslund´s (1936) height function:

$$H - 1.3 = d^{k} / (a + bd)^{k}$$

where H is height (m), d is DBH (cm) and k is a constant: k=2 for Scots pine (Näslund 1936) and birch (*Betula pendula* Roth and *B. pubescens*; Fries 1964) and k=3 for Norway spruce (Pettersson 1955). Parameters a and b were estimated by linear regression with DBH as the predicting variable. The dominant height was estimated using a height function based on the height corresponding to the arithmetic mean diameter of the 100 thickest trees ha^{-1}. Mean DBH was calculated as the diameter of the average basal tree and mean height according to Lorey´s mean height. Brandel´s (1990) volume functions for individual trees were used to estimate the total standing volume in each plot, and for trees with a DBH less than 4.5 cm Andersson´s (1954) volume functions were used.

Periodic annual stem volume increment (PAI) was calculated as the total annual production (including natural mortality) for selected trees (PCT experiment) and for all trees (thinning experiment) from the first thinning to the last assessment. In the thinning experiment, the annual basal area increment (BAI) was also calculated in the same manner as PAI. Long-term treatment effects on stand parameters (stems ha^{-1}, mean height, mean DBH, mean DBH of the 1400 thickest trees ha^{-1} 28 years after PCT, diameter distribution 22 years after thinning, basal area and total stem volume), annual mean increments (PAI, BAI, mean height- and mean DBH increments) and mortality rates were evaluated by analysis of variance, using the GLM procedure in the Minitab Statistical software (Minitab Inc. 2007), with the following model:

$$\gamma_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}$$

where μ denotes the grand mean and ε_{ij} is the error term *NID* $(0, \sigma^2)$. Block effects (βj) were considered to be random, and treatment (α_i) effects were considered to be fixed. Tukey's test was used to identify significant differences ($p \leq 0.05$) between treatments. Since the two PCT sites were in different growing phases, the results from these sites were analyzed separately in order to avoid allometric effects.

3.2 Paper II

The experimental site (Table 1) is located on a south-southwest facing slope of approximately 20 degrees and the dominant species in the field layer is bilberry (*Vaccinium myrtillus*). The soil texture is moraine, a bit coarser than sandy-till according to Hägglund and Lundmark (1987). The stand originates from direct seeding of lodgepole pine (0.4 kg ha^{-1}) after harrowing in 1992 and the resulting number of seedlings per hectare varied between 8000 and 10000.

The field experiment was established in September 2006 and consists of two blocks, each with seven 400 m^2 experimental plots and two plots of 700 m^2 in each block. The size of each net plot is 20 x 20 m, and 20 x 35 m respectively, with a 2.5 m buffer zone around each plot. PCT to achieve the stand stem density target for each regime was performed in July 2007. The treatments in the 400 m^2 plots were as follows: (i) High biomass, no PCT; (ii) Large dimension, PCT to 1700 stems ha^{-1}; (iii) Conventional, PCT to 2200 stems ha^{-1}; and (iv) Combined, PCT to 4500 stems $ha^{-1.}$ In addition, in the two 700 m^2 plots, the treatment was High biomass and in these plots two corridor FBT treatments were applied in June 2012.

The corridors were created perpendicular to the direct seeding rows, resulting in clusters of trees. In both treatments, the removal level was about 70% of the total area, with the aim of creating a tree cluster density after thinning corresponding to the remaining stem number per hectare created by conventional first thinning. The width of the corridors was 0.7 and 1.4 m and the unthinned strips left between corridors were 0.3 and 0.6 m, respectively. The thinning was carried out manually in order to avoid machine-related damage. Strip roads were located every 20 m (i.e. one strip road in the middle of each plot).

All plots in the study area were inventoried in 2011. Plots subjected to corridor thinning were re-measured before (June) and after (September) harvest in 2012. DBH (1.3 m height) was recorded (mm) for all trees within the net plots. The tree height of selected trees (five of the tallest trees and an additional 20-30 sample trees per plot representing all DBH-classes) were measured (dm) and height curves were constructed using Näslund`s equation (1936). Stem volume for lodgepole pine was estimated using function no 21 presented by Eriksson (1973). Stem volumes of Scots pine, Norway spruce and birch were estimated as in paper I. For Scots Pine, Norway spruce and birch Marklund´s (1988) functions were used to estimate tree biomass in terms of dry weight (kg). Different functions for stem, branches and needles for each species were used, see Marklund (1988) for details. Local biomass functions were constructed for lodgepole pine after destructive biomass harvest of 29 sample trees. Representative tree sizes were determined based on diameter at breast height. Biomass functions were constructed for the stem including bark, and for the total tree including stem, bark, branches, foliage and dead branches. The functions were fitted using the Minitab Statistical software (Minitab Inc. 2007). For further details see Ulvcrona (2011).

Treatment effects on stand parameters basal area, stem volume, biomass, dominant height, mean diameter, mean diameter of future crop trees and damage, were evaluated by analysis of variance, using the GLM procedure in Minitab Statistical software (Minitab Inc. 2007) with the model also used in Paper I.

3.3 Paper III

Treatments of various magnitudes were selected at Scots pine sites with similar SI, comparable altitudes within the same geographical region (Table 1) in order to represent three major types of silvicultural regime. The regimes considered were: (i) Dense = a continuous high stand stem density (ii) Sparse = a continuous low stand density; and (iii) Dense/Sparse = a high initial stand density followed by high intensity PCT/commercial thinning.

Within each regime, six to nine sample trees were cut. For every sample tree, 20–30 cm thick stem discs were removed at breast height (1.3 m), at the height of the living crown (i.e. the lowest living branch not surrounded by two or more dead branch whorls) and at 20% and 70% of the total tree height. The following characteristics of stem discs were recorded: diameter, number and width of annual rings and proportions of earlywood and latewood, using a commercially available scanner and the software package WinDENDRO™. From the stem discs, two approximately 3 mm thick wood sticks were sawn in the radial direction (from pith to bark), orientated north-south in relation to the original position of the trees. The sticks were divided in the longitudinal direction at every third year ring, counting from the pith and moving outwards to ring number 36. Thus, specimens containing three annual rings were taken in order to represent different cambial ages within the first 36 rings.

All specimens were visually inspected for the presence of compression wood. In the cases of obvious occurrence, specimens were not further analysed. For the remaining specimens, fibre extraction and removal of wood components were carried out in accordance with the work by Franklin (1945) and Fries et al. (2003). Specimens were placed in test tubes with a mixture of equal volumes of hydrogen peroxide (H_20_2) diluted to 25% and concentrated acetic acid (CH_3COOH). Test tubes were placed in an oven (70°C) until the wood was pale, which took approximately 24–30 hours. Once the specimens were removed from the oven, they were washed three times in water before being shaken until a homogenous fibre suspension was formed. The suspensions were then analysed using a Kajaani FiberLab 3.0 analyser (Metso Automation Inc., Kajaani, Finland). Between every run, each piece of equipment was rinsed in order to avoid sample contamination. For calibration, every tenth specimen was analysed three times. In order to eliminate the influence of small fragments, length-square-weighted mean length (Fries et al. 2003) was calculated. After visual examination of pictures taken when collecting the measurements, the maximum fibre length was set to 4.0 mm and the minimum length to 0.3 mm. Functions expressing fibre length development over time were fitted for the interval 0.3–2.8 mm. For simplicity, in order to keep the number of function expressions at a workable level, two different expressions were used:

$$y = a + bz$$

$$y = a + bz - cz^2$$

where y is the fibre length, z is the growth ring number (counted from the pith outwards), a is the intercept and b and c represent the slope of the expression. A suitable expression was determined using the standard deviation of the fitted line. The fibres were divided into three length classes: < 1.5 mm, 1.5–2.5 mm and > 2.5 mm representing JW, TW and MW respectively (Boutelje 1968). Transition ages at 1.5 mm and 2.5 mm were found by setting *y* equal to 1.5 and 2.5 in the expression used for fibre length development above. For each individual tree and sample height, the arithmetic means of fibre length (x) were calculated within each of the three defined length classes. Thus, it was assumed that the fibre length would not increase (or decrease) substantially outside the sample area. Total mean fibre length was then calculated as:

$$\bar{x}_{jh} = \frac{\sum_{i=1}^{n} P_i \times x_i}{\sum_{i=1}^{n} P_i}$$

where $\bar{x}$ is the weighted arithmetic mean fibre length for tree j at height h and P is the proportion of total tree radius and $i = 1\ldots,n$ is fibre length class.

In order to calculate the volume and volume proportion of each fibre length class, the trees were divided into five sections, with the sampling heights representing the boundaries between the different sections. Thus, the stem sections were: (i) 0–1.3 m (Base); (ii) 1.3 m to 20% of total tree height (Stem 1); (iii) 20% of total tree height to the height of the living crown (Stem 2); (iv) height of the living crown to 70% of total tree height (Stem 3); and (v) 70% to 100% of total tree height (Top). Volume calculations were largely in accordance with the work of Alteyrac et al. (2006). The radii of fibre length classes (*FLCR*) were used in calculations of fibre length class volume ($FLCV_{ijh}$) and were calculated as:

$$FLCR_{ijh} = \sum_{a=pith}^{a=TA} RW$$

where TA_{ijh} is the transition age at fibre length i in tree j at sampling height h and RW is the ring width. Two different transition ages were used: i = 1.5 mm and i = 2.5 mm. Tree radius (TR) was used for calculations of total volume ($TotVol_{jh}$) and was calculated as:

$$TR_{jh} = \sum_{a=pith}^{a=bark} RW_a$$

where RW is the ring width at cambial age a.

In order to calculate fibre length class volume ($FLCV_i$) for class i and total volumes, the formulas for a cylinder (Base), a truncated cone (Stem 1 – Stem 3), and a cone (Top) were used. Total tree volume and total volume in fibre length class i was calculated as the sum of volume in all stem sections. For i = 1.5–2.5 mm (TW zone), the volume was calculated as:

$$FLCV_{i=2.5jh} - FLCV_{i=1.5jh}$$

For i = > 2.5 mm (MW zone), the volume was calculated as:

$$TotVol_{jh} - FLCVol_{i=2.5jh}$$

Finally, the volume proportion of fibre length class i ($FLC_{prop}Vol_{ij}$) was calculated as:

$$FLC_{prop}Vol_{ij} = 100 \times \frac{FLCVol_{ij}}{TotVol_j}$$

Mean fibre length and ages of demarcation between the identified fibre length classes were analysed at the different sample heights; wood type volume ha^{-1} and wood type volume proportions were also compared. Treatments within the same silvicultural regime were compared in order to determine whether they differed significantly and whether the division into regimes was relevant. Thereafter, comparisons were made, first between treatments and, second, between regimes, using the GLM procedure in the Minitab Statistical software (Minitab Inc. 2007), Differences were analysed using Tukey´s test.

3.4 Paper IV

Five experimental sites supporting natural regenerated Scots pine were used for the purpose of paper IV. Originally, at each site, two different treatments were applied: PCT (at dominant heights 2-5 m) leaving 2500 stems ha^{-1} and control (no PCT). The plots where PCT was applied were used in simulations of a “conventional” management regime hereafter referred to as CONV. In the control plots, a first biomass thinning (FBT) was simulated at two different mean stand heights; 6–7 m (BIO1) and 8–9 m (BIO2). However, from one site (plot 971), complete stand data was missing below mean stand height 8.9 m and therefore BIO1 treatments were omitted from that site. On each occasion, thinning simulations aimed to achieve a stand density after thinning amounting to 4000 stems ha^{-1}. Schematic thinning was simulated by applying the same thinning intensity for each tree species DBH class. Thinning intensities that were applied in order to reach the stand stem density target varied from 65 to 80% of the total area.

Stand growth development from the time of FBT was simulated in five-year periods using functions developed by Söderberg (1986). In the growth simulations, the thinning response (dependent on site quality, removed basal area and time since treatment) was estimated using functions developed by Jonsson (1974). After FBT, the calculated thinning response was distributed at trees adjacent to strip roads/corridors to mimic the results of Bucht (1981). It was assumed that 40% of the trees remaining after FBT were affected by a thinning response caused by edge-effects associated with the strip roads/corridors. The growth reaction of these trees was divided into two categories, 0–1.5 m and 1.5–3 m distance to a strip road/corridor (50% allocated to each category). The trees that were affected by edges and to what degree (i.e. allocated category) were selected randomly. In order to account for growth losses associated with whole-tree removal during FBT, the yield of the subsequent first pulpwood thinning (PFT) operation was reduced by 8% (Helmisaari et al. 2011). Natural mortality was simulated as density-dependent (Söderberg 1986) and as a stochastic process (Bengtsson 1978, Bengtsson 1980). Conventional thinning activities and final felling were timed and simulated using general thinning guidelines (Anon. 1985a, Anon. 1985b).

Operational costs were calculated as presented in Table 2. Amounts of biomass were calculated according to Marklund (1988). Stem volumes over bark were calculated using functions proposed by Söderberg (1986). Stem volumes under bark were derived using the relationship between volume over and under bark defined by Brandel (1990). The proportion of merchantable wood obtained during thinning and final felling was calculated according to Ollas (1980). Timber- and pulpwood prices were calculated as the mean price (SEK /m^3 solid under bark) offered by Swedish forest companies and forest owner associations (Anon. 2013). The price for pulpwood was set to 248 and for timber 386 SEK m^3/solid under bark. The price for whole-tree biomass assortments was set to 400 SEK/ ton dry weight (Skellefteå Kraft Corp. 2013).

Total stem volume in stand *i* was divided by the total amount of biomass in order to derive a conversion rate between biomass and stem volume for each individual stand. The harvest cost of FBT was divided by the price of biomass in order to determine the amount of biomass needed to break-even. By dividing first by the average tree size and second by the total stem number, the harvest intensity, expressed as a percentage of the total stem number needed to be harvested in order to break-even in FBT was derived. In order to estimate regime profitability and to compare management regimes, the *LEV* was calculated. No taxes were included in the analysis.

Table 2. Operational costs and time consumption models used in Paper V. SMH = scheduled machine hours (including delay times shorter than 15 min). PCT = pre-commercial thinning; FBT = first biomass thinning; PFT = first pulpwood thinning; LT = late thinning; FF = final felling; STF = seed tree felling

Operator	Treatment	Cost (SEK SMH^{-1})	Time consumption model
Manual	PCT	300	Anon. (1991)
Harvester	FBT	1157	Bergström (2009)/Bergström and Di Fulvio (unpubl.)
Bundle-Harvester	FBT	1638	Bergström (2009)/Bergström and Di Fulvio (unpubl.)
Harvester	PFT	910	Bergström (2009)/Bergström and Di Fulvio (unpubl.)
Harvester	LT/FF (STF)	1000	Brunberg (1997)/Brunberg (2007)
Forwarder	FBT/PFT	746	Bergström (2009)/Bergström and Di Fulvio (unpubl.)
Forwarder	LT/FF (STF)	900	Brunberg (2004)
Disc trencher	Soil preparation	1815*	Brunberg (2011)**

*SEK ha^{-1}
** Reference

3.5 Paper V

This study made use of both a questionnaire survey regarding wood-based product market potentials and an analysis of electricity prices and wood raw material prices. In late February 2011, the questionnaire was posted to 102 individuals from industry, universities and business organizations, who we were informed all worked on wood product-related issues. The questionnaire consisted of two parts with, in total, 16 questions, some of them with sub-questions (a, b, c…). The first part contained three questions in which the respondents were asked to estimate potential values of wood biomass and biorefinery products in general. The second part contained 13 questions in which the respondents were asked to describe promising lignocellulosic products and estimate product development, raw material need and electricity demands linked to these products.

Changes in the Swedish mean annual electricity and wood fuel prices between 2000 and 2011 were monitored. The correlation between them was tested by linear regression and Pearson correlation in the Minitab Statistical software (Minitab Inc. 2007), Electricity prices for Swedish industry expressed in 2011 prices (SEK MWh^{-1}), including energy tax, were obtained from the Swedish Energy Agency official statistics (Anon. 2012c). Wood fuel price refers to the mean real price (excluding tax) of assortments: densified wood fuels (pellets and briquettes) for thermal heating, wood chips for industrial use and district heating and by-products (wood chips, bark and sawdust) for industry and district heating. Wood fuel prices were expressed in terms of 2011 prices (SEK MWh^{-1}) and were obtained from the Swedish Energy Agency official statistics (Anon. 2012d).

Coniferous timber and pulpwood prices from 1995 to 2012 were obtained from the official statistics of the Swedish Forest Agency (Anon. 2012b). The annual timber prices presented refer to the mean price of Scots pine and Norway spruce delivery logs. All prices were converted from SEK to Euro using a rate of 0.11, this being the rate on 12th of February 2013. Prices of actual assortments were originally expressed in m^3 solid under bark and in some cases in tonnes. The ash content and basic densities of wood assortment were defined according to the literature review compiled by Ringman (1996). For each assortment, the net calorific value (W_{eff}) expressed in MWh ton^{-1} was calculated as described by Hakkila (1989). In order to calculate the energy content, W_{eff} was multiplied by the weight in tonnes. Thereafter, prices in original units were converted to MWh $Euro^{-1}$.

4 Results & discussion

4.1 Development of stand and tree characteristics in different PCT and thinning regimes (I, II, III)

PCT is typically carried out selectively in young stands in order to create production units containing about 2000-2500 stems ha^{-1}. This approach is generally considered well suited if the overall goal is to produce pulpwood and timber and to achieve high revenues from harvests performed late in the rotation period. It was shown that the form (study I) and intensity (study II) of PCT strongly influence mean DBH and individual tree growth (as defined by the mean tree volume; Tables 3 and 4). In study I, selective PCT to achieve low stem numbers significantly and positively influenced the mean DBH compared to the control and corridor PCT treatments. Performing a selective PCT in naturally regenerated Scots pine stands at a dominant height of 3 m will, according to Huuskonen and Hynynen (2006), increase mean stand DBH by 15% (compared to no PCT) by the time the dominant tree height reaches 14 m. In study II it was shown that the intensity of selective PCT operations is an important tool for manipulating the mean DBH of a stand. DBH growth typically increases with decreasing number of stems ha^{-1} (Sjolte-Jørgensen 1967, Peltola et al. 2002). Previous studies have also shown that mean DBH and DBH increment generally increase with increases in PCT intensity (Varmola and Salminen 2004, Johnstone 2005, Huuskonen and Hynynen 2006).

Table 3. Stand stem density and growth characteristics of stands subjected to each of the treatments at an intermediate site type (IntSI) 27 years after PCT and at a poor site type (LowSI) 29 years after PCT. N = number of stems, DBH = mean diameter at breast height, Ba = mean basal area, V = mean stem volume, H_i = yearly mean height increment, DBH_i = yearly mean diameter increment, and M = mortality. Different letters indicate significant within-site differences ($p \leq 0.05$) (Paper I)

Treatment	N ha^{-1}	DBH (cm)	Ba ($m^2\ ha^{-1}$)	V ($m^3\ ha^{-1}$)	H_i * (m $year^{-1}$)	DBH_i * (mm $year^{-1}$)	M* (stems $ha^{-1}\ year^{-1}$)	M* ($m^3\ ha^{-1}\ year^{-1}$)
IntSI								
C	7020^{a}	9.2^{b}	44.3^{a}	303.3^{a}	N.a.	N.a.	N.a.	N.a.
Cor57	5121^{ab}	9.2^{b}	33.3^{b}	204.7^{b}	0.33^{b}	2.90^{c}	59.5^{a}	0.80^{a}
Cor65	3399^{ab}	11.1^{b}	33.1^{b}	225.8^{b}	0.39^{a}	3.50^{bc}	29.5^{a}	0.20^{a}
Cor73	3236^{ab}	11.5^{b}	31.6^{bc}	209.4^{b}	0.36^{ab}	3.56^{bc}	59.5^{a}	0.50^{a}
Cor79	2928^{ab}	11.2^{b}	28.9^{bc}	197.0^{b}	0.38^{ab}	3.72^{ab}	14.5^{a}	0.00^{a}
Cor82	3156^{ab}	11.9^{b}	29.5^{bc}	198.0^{b}	0.39^{ab}	4.08^{ab}	15.0^{a}	0.15^{a}
S1400	1484^{b}	15.2^{a}	26.8^{bc}	180.9^{b}	0.36^{ab}	3.80^{ab}	30.0^{a}	0.25^{a}
S1000	1083^{b}	16.8^{a}	24.2^{c}	165.6^{b}	0.37^{ab}	4.32^{a}	0.0^{a}	0.00^{a}
LowSI								
C	7944^{a}	6.0^{c}	22.6^{a}	96.8^{a}	N.a.	N.a.	N.a.	N.a.
Cor57	4113^{b}	7.0^{c}	15.8^{b}	74.2^{a}	0.21^{b}	2.27^{c}	141.0^{a}	0.35^{a}
Cor65	4737^{b}	6.7^{c}	16.6^{b}	75.6^{a}	0.21^{b}	2.38^{c}	106.5^{a}	0.45^{a}
Cor73	4174^{b}	6.8^{c}	15.3^{b}	70.2^{a}	0.22^{ab}	2.36^{c}	70.0^{a}	0.25^{a}
Cor79	4142^{b}	6.9^{c}	15.2^{b}	67.9^{a}	0.20^{b}	2.43^{c}	117.5^{a}	0.15^{a}
Cor82	3639^{b}	7.2^{c}	14.8^{b}	68.7^{a}	0.21^{b}	2.52^{c}	193.0^{a}	0.45^{a}
S1400	1710^{c}	10.1^{b}	13.6^{b}	68.6^{a}	0.22^{ab}	2.84^{b}	216.5^{a}	0.50^{a}
S1000	1105^{c}	12.1^{a}	12.8^{b}	71.4^{a}	0.30^{a}	3.30^{a}	107.5^{a}	0.55^{a}

* Mean values of selected crop trees. N.a. indicates “not analyzed”.

Table 4. Regime means of basal area, stem volume, biomass, number of stems ha^{-1}, dominant height, mean diameter at breast height weighted against basal area (Dgv), mean Dgv for the 1000 and 2000 largest lodgepole pine trees ha^{-1} for each treatment after the autumn 2011 inventory. Means with different letters are different at the 0.05 level of significance according to Tukey´s multiple comparison test (Paper II)

Silvicultural regime	Number of stems (ha^{-1})	Dgv (cm)	Dgv 1000 largest trees ha^{-1} (cm)	Dgv 2000 largest trees ha^{-1} (cm)	Basal area (m^2 ha^{-1})	Stem volume (m^3 ha^{-1})	Biomass (ton ha^{-1})	Dominant height (m)
Conventional	2150	8.0^b	8.9^a	8.0^a	9.3^c	31.5^b	21.6^c	7.2^a
High biomass	15331	6.2^c	8.8^a	8.1^a	21.4^a	73.9^a	52.8^a	7.6^a
Large dimension	1663	8.9^a	9.6^a	-	8.8^c	30.4^b	20.6^c	7.5^a
Combined	4481	7.7^b	9.6^a	8.7^a	16.1^b	63.0^a	39.5^b	7.7^a

When mean DBHs are being discussed, the total number of stems in the stand has a great influence. Comparisons of the mean DBHs of the 1000–2000 largest trees ha^{-1}, can add further information as these stems represent most of the future crop trees in a stand. In study II, the mean DBH of the 1000 and 2000 largest trees ha^{-1} was not significantly different between regimes (Table 4). In study I, comparisons of the 1400 thickest trees ha^{-1} at the time of the last measurement revealed only minor differences between all the treatments included (Figure 1). According to Binkley et al. (2010), the dominant trees within a stand use the available resources better than the small trees and they are also able to produce more stem wood per unit of light. Therefore, the initial size of a tree before it is exposed to competition corresponds rather well to its relative size within the stand at the time of the first commercial thinning (Nilsson and Albrektsson 1994). Thus, biomass growth of individual trees will largely depend on the tree’s hierarchical status within the stand and the size of the dominant trees in dense pine stands might be about equal to the size of the dominant trees in stands subjected to PCT, as shown also by Ulvcrona (2011).

After selective PCT, the size of the trees in the remaining stand becomes more even and the total diameter increment is often greater than if the trees are left in clusters, lines or rows (Burns and Puettmann 1996, Mäkinen et al. 2006). In schematic PCT, tree removal is evenly distributed amongst DBH classes whereas a selective PCT mainly focus on the removal of trees in smaller DBH classes. Therefore, the remaining trees are, on average, larger after a selective PCT than after a corridor PCT. After a thinning, the remaining trees tend to increase their diameter growth, mainly in the lower part of the stem (Valinger 1992, Peltola et al. 2002). The absolute diameter growth response after thinning is often greatest amongst the largest trees (Peltola et al. 2002). In study I, the mean DBH increment was also reduced after corridor PCT/thinning compared to selective methods. Thus, differences in mean DBH were still apparent at the end of the study period. In study I, corridor PCT did not result in a long-term improvement in mean DBH compared with the control plots. However, improvements (compared to no thinning) in DBH increment after corridor thinning have previously been detected in several studies (Little and Moore 1963, Bella and Franceschi 1982, McCreary and Perry 1983, Burns and Puettmann 1996, Pelletier and Pitt 2008).

In general, low intensity or no PCT will favor volume growth and the amount of biomass available (Pettersson 1993, Karlsson et al. 2002). Substantial amounts of biomass and stem wood volume were also produced both in study I (control) and in study II (High biomass) when PCT was not undertaken. In study II, the High biomass regime produced ca 144–157% more biomass and 134-143% more stem volume than regimes including PCT to 2200 and 1700 stems ha^{-1} (Conventional and Large dimension regimes; Table 4). In study I at the IntSI site, the standing volume in control plots exceeded that in corridor PCT plots by 34–54% and selective PCT by 68–83% (Table 3). At the LowSI site, the standing volume was also greatest in the control plots (28–43% higher than in the corridor PCT plots and 36–41% higher than in the selective PCT plots), but no significant between-treatment differences were found at the site (Table 3). Thus, the short-term effects of a regime aiming to maximize biomass production seen in study II for lodgepole pine were consistent in the long-term (about 30 years) with the Scots pine stands investigated in study I. Compared with a selective PCT, the “high biomass strategy” in both studies resulted in high stem numbers and a reduced mean DBH. Using a combined approach which included PCT to 4500 stems ha^{-1} resulted in substantially more biomass (83%) than a conventional management regime without significantly reducing mean DBH and may, therefore, offer multiple opportunities for the forest owner.

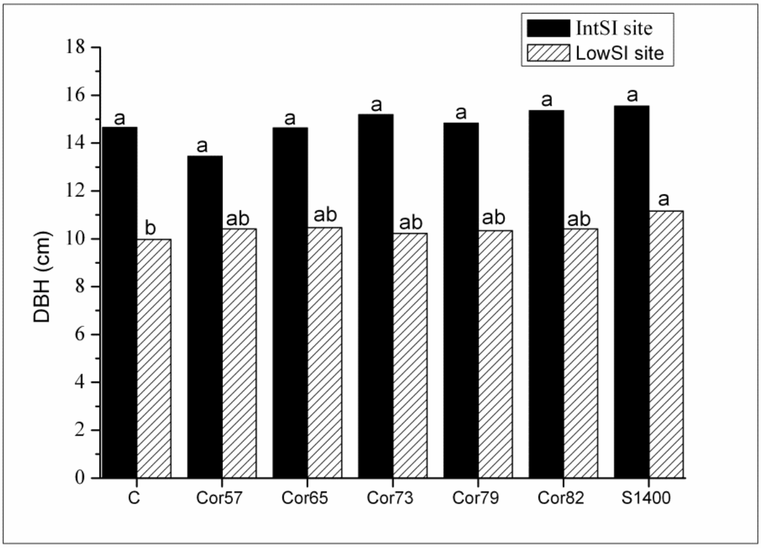

Figure 1. Mean diameter at breast height (DBH) of the 1400 thickest Scots pine trees ha^{-1} (at the time of the last assessment) after no PCT (C), corridor PCT (Cor) with corridor areas of 57, 65, 73, 79 and 82% (Cor57-Cor82, respectively) and selective PCT (S) to 1400 stems ha^{-1} (S1400). Different letters indicate significant differences ($p \leq 0.05$) within-site (average over two blocks; Paper I).

Study III demonstrated that the initial environmental conditions that a Scots pine is exposed to can influence also the properties of wood raw material derived in late thinning and final-felling operations. At the breast height of all individual trees, MW was formed within 17–28 years**;** this corresponds to previous findings for Scots pine (Sauter et al. 1999, Fries et al. 2003, Mutz et al. 2004). On average, the regimes with high initial stand densities formed MW at breast height on average six years earlier than the regime with low initial stem numbers (Table 5). Similar results pertaining to the effects of the initial spacing have been presented for Norway spruce (Kucera 1994) and Scots pine (Eriksson et al. 2006). However, results presented for *Pinus eliottii* (Clark and Saucier 1991), *Pinus taeda* (Clark and Saucier 1991), *Picea glauca* (Yang 1994) and *Picea mariana* (Yang 1994, Alteyrac et al. 2006) contradict this finding.

Generally, fibre length increases with age until the mature fibre length is reached. Thereafter, fibre lengths do not substantially increase or decrease (Bendtsen and Senft 1986, Kucera 1994). In study III, initial fibre length development occurred more rapidly in dense stands. In general, relatively long fibres are produced at low radial growth rates (Zobel and van Buijtenen 1989, Sirviö and Kärenlampi 2001, Mäkinen and Hynynen 2012). However, the opposite relationship has been showed by Bergquist et al. (2000), whilst Stairs et al. (1966) found no significant effect of growth rate on fibre length. The proportion of MW was substantially higher in trees from the initially dense stands (about 60%) than in trees from the sparse stands (about 34%) investigated (Figure 2). In PCT, low quality trees and non-preferred tree species can be removed and the operation is therefore generally considered to improve the overall wood quality of a stand (Pettersson 2001). However, the results presented here indicate that wide spacing during planting and/or early PCT to low stem numbers might be associated with short wood fibres (Figure 3) and low proportions of mature wood (Figure 2). Therefore by applying appropriate initial management regimes, high quality wood and fibres for specific end-uses could be produced. This approach would mean that less focus on high volumes would be needed within the forest industry.

After undertaking a high intensity thinning in dense stands, the proportion of JW amounted to 2.5–5% at tree ages of about 50 years. Corresponding proportions were 4–9% and 4.5–16.5% in stands with continuously high and low stem numbers respectively (Figure 2). It has also previously been suggested by Zobel and van Buijtenen (1989) and Pape (1999) that the proportion of JW might be kept at a low level if initially slow-growing trees are retained in the stand after thinning. Solid wood products containing JW may be unstable due to its typical features (short fibres, large Mfas and low wood density; Pearson and Gilmour 1971, Harris 1981, Bendtsen and Senft 1986, Saranpää 1994). The high lignin content, the low proportion of cellulose and the high moisture content in JW (Uprichard and Lloyd 1980) mean that it requires a complicated and expensive pulping process. Chemical pulp yields per unit volume have been reported to be reduced by 5–15% when JW is used (Kirk et al. 1972, Zobel and Sprague 1998). The short JW fibres with thin cell walls produce pulp with low tear strength properties, low opacity, and high tensile and burst strength (Kirk et al. 1972). Thus, a high intensity thinning in young, dense Scots pine stands seems to have positive effects on the traditional end-use of wood raw materials.

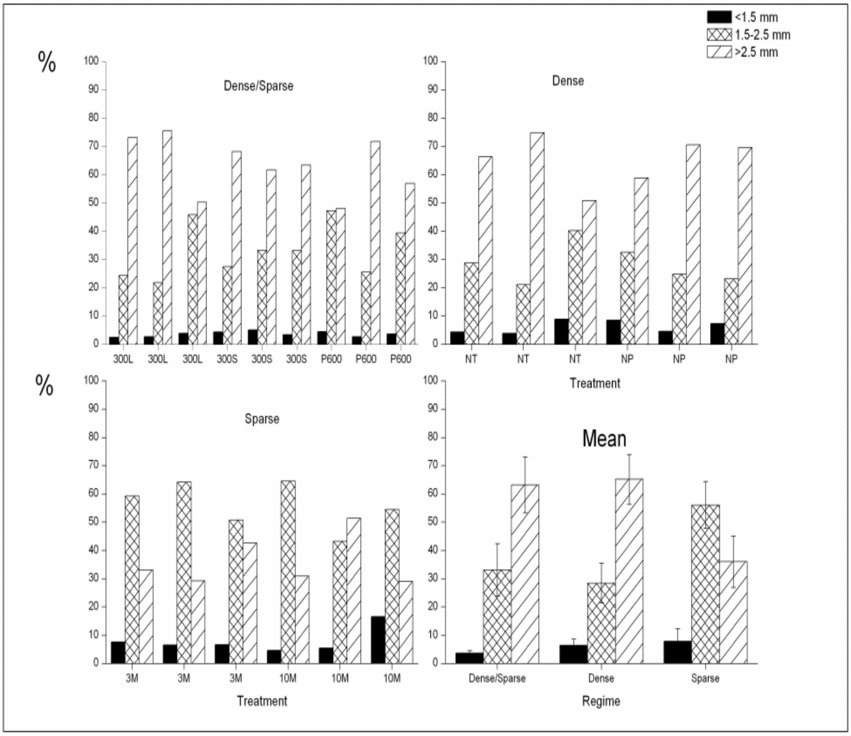

Figure 2. Volume proportions of different fibre length intervals in all trees examined in each regime and mean values for the different principal management regimes (Dense/Sparse = a high initial stand density followed by high intensity pre-commercial thinning/commercial thinning, Dense = a continuously high stand stem density and Sparse = a continuously low stand stem density); bars denote standard deviations. 300L = thinning leaving the 300 largest trees ha^{-1}; 300S = thinning leaving the 300 smallest trees ha^{-1}; P600 = PCT to 600 stems ha^{-1} at a dominant height of 5m; NT = no thinning; NP = no PCT; 3M = 3m spacing; 10m = 10m spacing (Paper III).

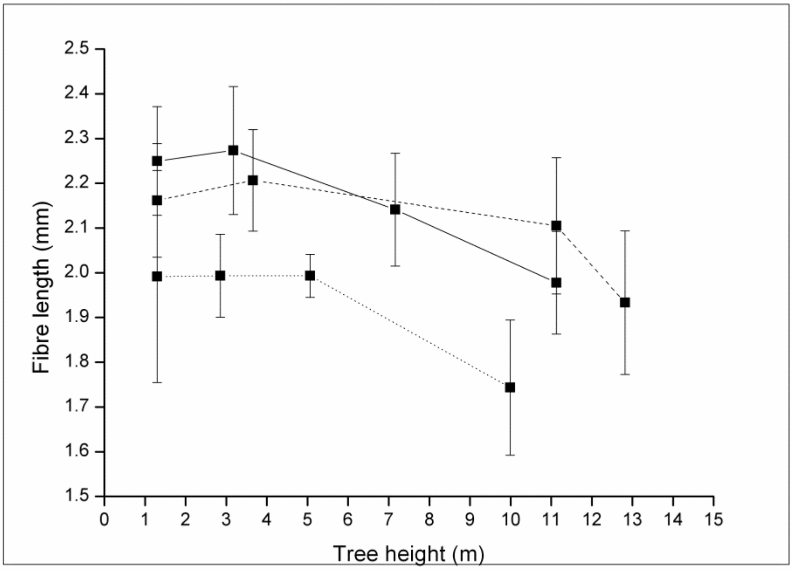

Figure 3. Mean fibre length at the sample heights for the management regimes examined. Solid line represents Dense/Sparse (= a high initial stand density followed by high intensity pre-commercial thinning/commercial thinning), dashed line represents Dense (= a continuously high stand stem density) and dotted line denotes Sparse (= a continuously low stand stem density); bars denote standard deviations (Paper III).

Table 5. Number of annual rings and mean ring width within different fibre length classes at breast height (BRH) and 20% of total tree height for the regime types examined. Different letters indicate significant differences. Dense/Sparse = a high initial stand density followed by high intensity pre-commercial thinning/commercial thinning, Dense = a continuously high stand stem density and Sparse = a continuously low stand stem density (Paper III)

Regime type	0.3–1.5 mm		1.5–2.5 mm		> 2.5 mm
	No of years	Ring width (mm year^{-1})	No of years	Ring width (mm year^{-1})	Ring width (mm year^{-1})
BRH					
Dense	6.24^{ab}	2.75^{a}	12.54^{a}	1.98^{b}	0.89^{b}
Dense/Sparse	4.99^{b}	2.69^{a}	14.03^{a}	2.73^{ab}	1.54^{a}
Sparse	8.78^{a}	3.40^{a}	16.17^{a}	2.92^{a}	1.35^{a}
20%					
Dense	4.59^{b}	3.51^{a}	8.56^{c}	2.46^{a}	0.98^{b}
Dense/Sparse	4.63^{b}	3.45^{a}	11.44^{b}	3.03^{a}	1.55^{a}
Sparse	6.94^{a}	3.64^{a}	15.18^{a}	2.29^{a}	1.36^{a}

4.2 Development of stand and tree characteristics after early schematic thinning (I, II, IV)

Once corridor harvesting has been undertaken, the DBH growth of trees standing in the vicinity of corridors increases (Hamilton 1976, Bucht and Elfving 1977, McCreary and Perry 1983, Mäkinen et al. 2006). The greatest growth reaction can be expected for the smallest trees (Bucht and Elfving 1977) and for trees facing a corridor in a southerly direction (Hamilton 1976, Bucht and Elfving 1977). The edge-effect typically extends 3–4 m into the stand (Bucht and Elfving 1977, McCreary and Perry 1983, Niemistö 1989, Mäkinen et al. 2006). Further into the stand, no growth reaction is detectable (Little and Mohr 1963, Hamilton 1976, McCreary and Perry 1983) therefore the growth of the edge-trees should compensate for the amount of biomass removed. Wide corridors generally have a positive influence on the growth of edge-trees, but a negative effect on the overall production as the number of edge-trees decreases (Hamilton 1976, Mäkinen et al. 2006). Thus, the growth after corridor thinning is highly dependent on the number of edge-trees or the proportion of edge-area.

In study I, corridor PCT treatments resulted in similar standing volumes to those after selective PCT (Table 3). At both sites, the periodic annual increment of corridor treatments was lower than after selective PCT (Figure 4). After 22 years the two thinning treatments undertaken at the first thinning stage had almost identical standing volumes. During the study period the volume- and basal area growth were, on average, 1.3% and 2.2% greater, respectively, after selective thinning, but these differences were not statistically significant (Table 6). Previously, five and 19-year effects of corridor thinning have been reported by Elfving (1985) and Mäkinen et al. (2006), respectively. Elfving (1985) observed a 3.5 and 6% growth reduction compared to selective thinning in Scots pine and Norway spruce, respectively. Corresponding figures reported by Mäkinen et al. (2006) amounted to 3 and 11%. There were generally small differences in standing volume between different proportions of corridor area (Table 3). At the most fertile site there were indications of that volume growth increased with increasing corridor area because 79 and 82% corridor areas differed significantly from the 59% corridor area (Figure 4). Due to the small differences in standing volume generally found in study I (Table 3, Table 6), it appears that volume production did not rely on the geometric distribution of the remaining trees. It has previously been shown that the distribution of trees within a stand has minor effect on the initial productivity of Scots pine (Salminen and Varmola 1993). Instead it appeared that stem volume production was much dependent on the total number of stems ha^{-1}, as reported also by Salminen and Varmola (1993). Optimal stand densities do likely vary between site types as they display different maximum sustainable leaf areas (Vose and Allen 1988).

Stand data from the last inventory in study I indicate only small differences between selective and corridor treatments in terms of size of the largest trees (Figure 1). Mean values of dominant trees in the remaining tree clusters in study II also indicated that fairly large trees were evenly distributed across the stands (Table 7). As shown in study IV, stands in which selective PCT has been replaced by a schematic FBT are likely to support a smaller average tree size in later harvest operations (Figure 5). However, no major mean differences in the total pulpwood and timber yield between conventionally managed stands and stands were PCT has been replaced by an FBT at stand heights of 6–7 and 8–9 m were detected in the simulations (Table 8). This is in line with previous findings by Heikkilä et al. (2009), who reported that early extractions of fuelwood did not decrease mean annual increments or the total yield of pulpwood and timber. At sites with a SI of 21–22, conventional management yielded more pulpwood but less timber than biomass thinning regimes over the rotation period. At higher site indices (26–28), more timber was harvested subsequently in the CONV regime than in the BIO regimes (Table 8). Consequently, applying a schematic FBT in young, dense pine stands does not seem to jeopardize the stand production substantially nor the ability to produce pulpwood and timber in later harvest operations. In all studies, corridor harvest was applied strictly schematically. Bergström (2009) suggested that 1 m wide boom-corridors directed at certain groups of trees could be applied in V- or fan-shaped patterns. Hence, the operation would still include some degree of selectivity. Therefore, the effects of the practical approach would probably be less than the ones reported here.

In Fennoscandia, a combination of snow and wind often causes damage and mortality in pine stands. Generally, the risk of damage varies with site-specific climatic conditions (Valinger and Fridman 1999) and increases immediately after thinning (Valinger and Lundqvist 1992). Trees with low stem tapering (Peltola et al.1997) and short, asymmetrical crowns (Valinger et al. 1993) are particularly susceptible to snow damage. In Japan, Satoo et al. (1971) noted significant amounts of snow damage after a schematic thinning. Therefore, caution should be applied when considering strictly schematic thinning in dense stands, especially at exposed sites. In study I no significant differences between treatments were found with respect to mortality volume (Table 3, Table 6). One year after corridor harvest in study II the proportion of damaged (the leaning/laying trees had increased from 3 to 10%) and dead trees had increased slightly but was not found related to corridor width (data not presented).

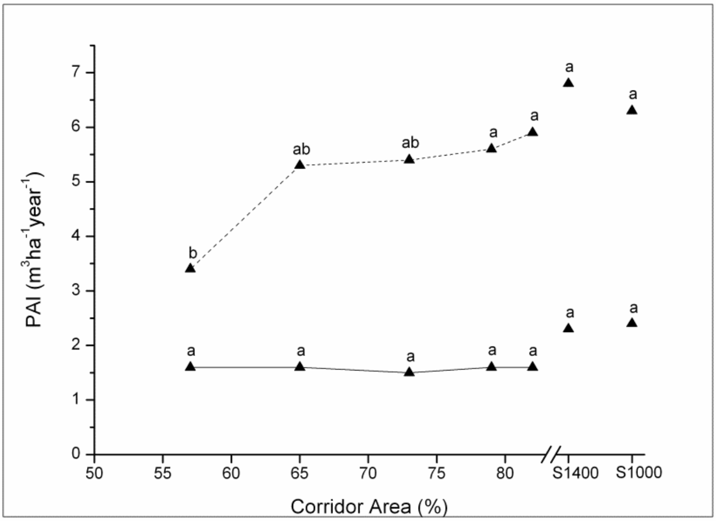

Figure 4. Periodic annual stem volume increment (PAI) of selected trees (considered as crop trees at establishment) in relation to pre-commercially thinned (PCT) corridor area, 29 years after PCT at the LowSI site (a poor site; solid line), and 27 years after PCT at the IntSI site (an intermediate site; dashed line). PAI values of trees remaining after selective PCT to 1400 (S1400) and 1000 stems ha^{-1} (S1000) are also shown. Different letters indicate significant differences ($p \leq 0.05$) within-sites (average over two blocks; Paper I).

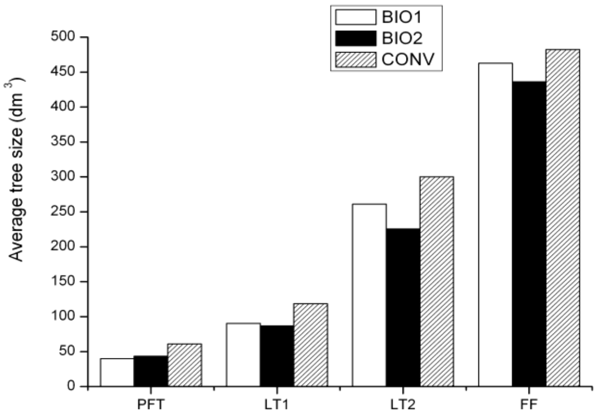

Figure 5. Average tree size harvested at first pulpwood thinning (PFT), late thinnings (LT1, LT2), and final felling (FF) in simulations of management regimes were pre-commercial thinning was replaced by a first biomass thinning conducted at average stand heights of 6–7 m (BIO1) and 8–9 m (BIO2) and a regime including pre-commercial thinning at dominant heights of 2–5 m (CONV; Paper IV).

Table 6. Treatment means for measured variables (ST = selective thinning, CorT = corridor thinning) and partitioning of effects according to Analysis of Variance (Paper I)

Variable	ST	CorT	Treatment (*p-value*)	Block (*p-value*)
Mean DBH (cm)	17.6	15.9	0.000	0.000
Stems ha^{-1}	1231	1492	0.000	0.000
Mean Height (m)	15.0	14.9	0.153	0.000
Volume (m^3 ha^{-1})	213.3	212.6	0.842	0.000
PAI (m^3 ha^{-1} $year^{-1}$)	8.1	8.0	0.531	0.000
BAI (m^2 ha^{-1} $year^{-1}$)	0.91	0.89	0.341	0.000
Mortality (stems ha^{-1} $year^{-1}$)	2.2	9.0	0.012	0.264
Mortality (m^3 ha^{-1} $year^{-1}$)	0.14	0.21	0.239	0.317
Mean DBH increment (mm $year^{-1}$)	3.42	3.14	0.002	0.000

PAI = Periodic annual increment
BAI = Basal area increment

The effects of corridor thinning on wood quality traits were not studied in detail. However, a strict schematic thinning would probably result in more potential crop trees being removed than in selective thinning. The stems left in corridors are typically closer together than after a conventional thinning. There might, therefore, be effects on both stem taper and branch diameter (Persson 1977). Lemmien and Rudolph (1964) did not discover any major differences in stem taper, size of branches and vitality between the main stems left after corridor- and selective thinning. Pettersson (1986), on the other hand, concluded that the benefits of actively choosing the main stems in selective PCT cannot fully compensate for the associated larger branch diameters compared to corridor PCT. Pettersson (1986) did also find that branches growing towards corridors were slightly thicker (not statistically significant) than branches growing towards the stand. Branches facing the stand will presumably experience lower levels of light and, therefore, are more likely to die off. As a result, trees will focus their shoot and branch growth towards the open space in corridors. In that case heavier loads might induce mechanical pressure, resulting in leaning trees, instability and basal sweeps. Stiell (1960) discovered basal sweep next to harvested corridors but concluded that the sweeps were insufficient to affect the timber quality adversely.

4.3 Timing, intensity and harvest potential of first biomass thinning operations (I, II, IV)

Study I showed that corridor thinning could be implemented at dominant heights of about 5 and 9 m without major reductions in subsequent growth and yield (Tables 3 and 6). Thus, schematic thinning may be useful for obtaining biomass from dense stands. After corridor PCT, there were small differences in standing volumes between different intensities (corridor areas; Table 3). The total corridor PCT area varied between 60 and 80% of the total area between treatments. It is, therefore, suggested that schematic FBT can be performed at various dominant heights and with high removal intensity as long as a substantial number of stems ha^{-1} are retained. It also appears that there is a certain amount of flexibility with respect to intensity when corridor thinning is conducted. Thus, there seem to be several alternatives available to the forest owner. Consequently, substantial amounts of biomass might be obtained by corridor thinning, without major reductions in volume growth if the total retained stem number is still high compared to conventional stand densities (i.e. about >3000 stems ha^{-1}).

Nilsson et al. (2010) have previously pointed out that the basal area after thinning in dense stands should be kept at a relatively high level in order to avoid production losses. Varmola and Salminen (2004) found a substantially reduced standing volume after PCT performed at a dominant height of 9 m leaving 1000 stems ha^{-1} compared to when 1600 and 2200 stems ha^{-1} were retained, but there were no differences between the two latter stand densities. Long-term effects of applying initial thinning at different heights have also previously been reported. For instance, Varmola and Salminen (2004) found no differences in standing volume between stands subjected to PCT at dominant heights of 6 and 9 m at a dominant height of about 15 m. Heikkilä et al. (2009) compared fuelwood thinning performance at dominant heights of 8–12 m and did not detect any major differences in subsequent growth between management alternatives.

In study II, a schematic FBT with an intensity of 70% was applied at a dominant height of 7 m in seeded lodgepole pine stands with stem numbers amounting to about 15000 ha^{-1}. As mortality rates were found to be rather low at that height, and mainly occurred amongst the smaller trees (not shown), FBT could probably have been performed at a greater dominant height. Amounts of biomass and stem volume harvested amounted to 30 oven dry tonnes (ODt) ha^{-1} and 45 m^3 ha^{-1}, respectively. The number of tree clusters ha^{-1} remaining after corridor harvest differed statistically with corridor width (almost twice as many in 0.7 m wide corridors than in 1.4 m corridors; Table 7). In study IV, corridor thinning retaining 4000 stems ha^{-1} was simulated at mean stand heights of 6-7 (BIO1) and 8-9 (BIO2) m in five stands with stem numbers ranging from 11000 to 20000 stems ha^{-1} (corridor area 64-80%). Removal levels in BIO1 and BIO2 amounted to 36-66 and 44-67 ODt ha^{-1}, respectively (Table 8). Given the current price price of 200 SEK ton^{-1} (400 SEK ODt^{-1}) and cost functions for boom-corridor thinning (Bergström 2009, Bergström and Di Fulvio unpubl.), the economic break-even harvest yield in FBT applied at 8-9 m amounted to about 32–44 ODt ha^{-1} (Figure 6). If the harvesting system included a bundle-harvester (Bergström 2009) corresponding harvest levels became 24–32 ODt ha^{-1} (Figure 6). Operational costs in FBT operations were largely dependent on average stem size and stand density. In naturally regenerated stands, the number of successfully regenerated seedlings typically increases with site quality parameters (Tegelmark 1998). Therefore, the harvest intensity required in FBT to break-even increased with site index in the BIO1 regime (Figure 7). However, crown closure and natural mortality occur earlier when site indices are high (Zeide 1987) and substantially reduce the stem number. As natural mortality will occur mainly amongst the smallest individuals (Weiner and Thomas 1986), the average tree size will increase further when competition reduces the stem number. Therefore, minimum FBT harvest intensities in BIO2 decreased with SI (Figure7).

Table 7. Harvest yield (Hy) and stand characteristics after corridor thinning in the High biomass regime, including number of trees (N) and tree clusters (N_c), and mean diameter at breast height (1.3 m) weighted against basal area (Dgv) for all trees in autumn 2012. Number of trees ha^{-1} with DBH >50 mm, and 80 mm, Dgv for the 1000 and 2000 largest trees (Dgv_{1000} and Dgv_{2000}) per hectare, and Dgv for dominant trees within retained tree clusters (Dgv_{dom}) based on all trees left after harvest. Means with different letters are different at the 0.05 level of significance according to Tukey´s multiple comparison test (Paper II)

Corridor width (m)	Hy (ton ha^{-1})	Hy (m^3 ha^{-1})	N	Dgv (cm)	N >50 mm	N >80 mm	Dgv_{1000} (cm)	Dgv_{2000} (cm)	N_c(ha^{-1})	Dgv_{dom} (cm)
0.7	32.0^a	44.5^a	4486^a	7.0^a	1507^a	400^a	8.4^a	7.5^a	1186^b	6.5^a
1.4	27.3^a	37.6^a	5879^a	6.5^a	1657^a	307^a	8.0^a	7.3^a	2186^a	5.4^a

Table 8. Timing (rotation year) of thinning (FBT/PFT/LT1/LT2) and final felling operations and total harvest yield for the different management regimes included in the study (Paper IV)

Regime	Timings of thinning	Timing of final felling	Whole-tree biomass from FBT (ODt ha^{-1})	Pulpwood (m^3 s ub ha^{-1})	Timber (m^3 s ub ha^{-1})
953					
BIO1	36/51/71	106	40.0	106.6	192.8
BIO2	41/56/76	111	51.4	103.7	193.7
CONV	52/77	107	-	118.3	168.1
954					
BIO1	34/49/69	99	36.3	111.0	180.1
BIO2	39/49/69	104	44.5	105.6	191.8
CONV	46/61	91	-	122.0	161.6
971					
BIO2	37/52/67	97	53.5	128.7	273.3
CONV	47/67	97	-	145.2	278.4
978:1					
BIO1	27/37/52/77	102	48.5	135.0	336.8
BIO2	35/45/60/80	105	67.1	146.6	314.0
CONV	37/52/72	92	-	143.5	350.7
978:2					
BIO1	27/37/52/67	92	66.5	141.3	354.0
BIO2	30/40/55/70	95	54.9	149.2	366.4
CONV	32/47/67	92	-	138.6	397.5

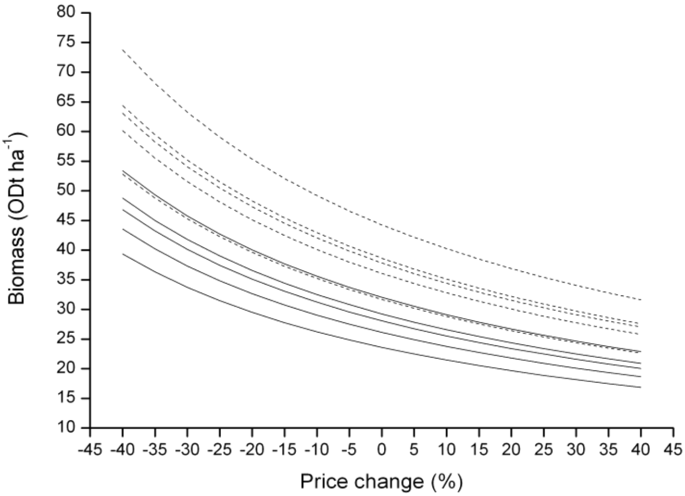

Figure 6. Amount of biomass that needs to be harvested in order to break-even financially at different price changes relative today's prices for whole-tree assortments (0%) in a first biomass thinning (applied at mean stand height 8–9 m) at the experimental sites. Cost-functions for innovative thinning systems for boom-corridor thinning with new felling technology (dotted lines) and in combination with integrated bundling (bundle-harvester; solid lines) were used (Paper IV).

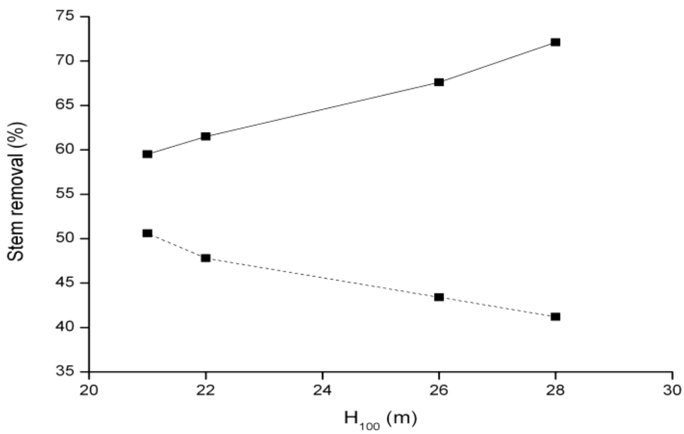

Figure 7. Harvesting intensity (percentage of the total number of stems (minimum height = 1.3 m) ha^{-1}) needed to reach break-even financially in first biomass thinning operations applied at 6–7 m (solid line) and 8–9 m (dashed line) in natural regenerated Scots pine stands using boom-corridor thinning at different site indices (Paper IV).

4.4 Profitability of PCT and thinning regimes (IV)

Using price levels from 2013 and a 3% interest rate, biomass thinning regimes generated a negative net present value in all cases from the first commercial pulpwood thinning and lower values than the conventional regime in subsequent harvest operations (Figure 8). This outcome was likely related to the average stem size harvested (Ahtikoski et al. 2008; Figure 5). Huuskonen and Hynynen (2006) previously reported gains in mean tree size and standing volume at a dominant height of 12 m compared to unmanaged stands (5000 stems ha^{-1}) after a “light PCT” (to 3000 stems ha^{-1}) at standard height (dominant height about 3 m). Similar results have also been presented by Varmola and Salminen (2004). Therefore, the “combined regime” approach presented in study II could generate high biomass yields in FBT but also a profitable first pulpwood thinning.

The large quantities of biomass harvested in FBT operations (Table 8) were found to contribute substantially to a high LEV. In general, BIO regimes resulted in higher LEV than CONV regimes, and BIO2 resulted in higher LEV than BIO1 (Figure 9). Including a bundler-harvester in the FBT harvest system resulted in an increase in LEV by about 15–30% for the BIO regimes. Conventional management yielded surprisingly low LEVs (Figure 9). This was mainly due to an expensive PCT because of high stem numbers. The results indicate that it may be beneficial to remove large amounts of biomass (and therefore not only small-sized trees) early in the rotation period. According to Ahtikoski et al. (2008), the cost associated with harvest in young, dense stands decreases with increases in biomass removal. Hyytiäinen and Tahvonen (2002) showed that it may be optimal to undertake the first thinning at high stand densities. Vettenranta and Miina (1999) suggested that it may be best to conduct high-intensity thinning from above at the time of maximum basal area growth. In general, the post-thinning reaction of suppressed trees remains rather unclear. However, Peltola et al. (2002) showed that the thinning response (i.e. an increased diameter growth after thinning) of small trees occurs more rapidly and is greater in relative terms compared to that of dominant trees. Nilsson et al. (2010) found no major long-term negative consequences of thinning from above instead of from below, indicating the difficulty of choosing optimal future value-trees in early selective operations.

Changes in interest rate did generally not alter the rankings between regimes. However, at a low interest rate (1%) the CONV regime became more competitive to BIO regimes (not presented). Hyytiäinen et al. (2006) also showed that investments in stand establishment and long-term timber supply are best suited at low interest rates. Profitability estimates of FBT operations were based on innovative harvesting systems and techniques (Bergström (2009, Bergström and Di Fulvio unpubl.). The results highlight incentives for continued technical development in order to realize the economic potential that seems to be associated with FBT harvest in dense stands.

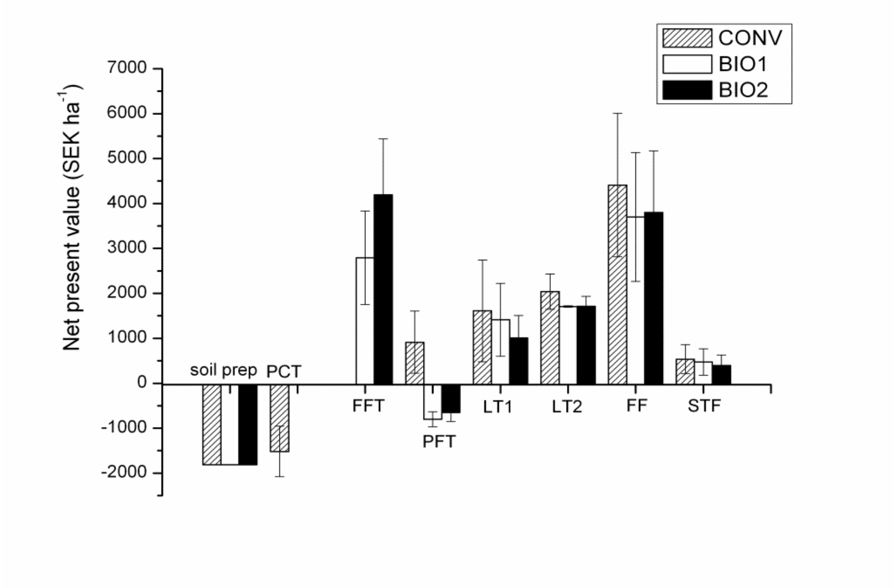

Figure 8. Mean net present value (site 971 excluded) discounted to rotation year 0 using a 3% interest rate and current assortment prices for each operation included in conventional (CONV) and first biomass thinning regimes (BIO1/BIO2), bars denote standard deviation. Soil prep = soil preparation; PCT = pre-commercial thinning; FBT = first biomass thinning; PFT = first pulpwood thinning; LT1/LT2 = late thinning; FF = final felling; STF = seed tree felling (Paper IV).

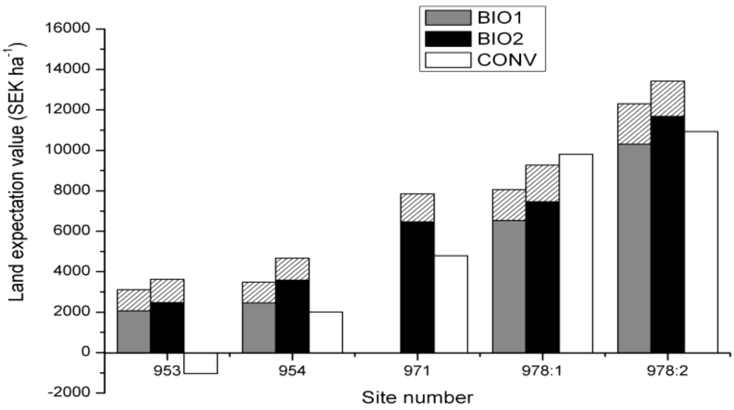

Figure 9. Land expectation value of silvicultural regimes, at a 3% interest rate and current assortment prices, simulated at five experimental plots. FBT = First biomass thinning undertaken at average stand heights of 6–7 m (BIO1) and 8–9 m (BIO2) in stands not subjected to pre-commercial thinning (PCT); CONV = conventional management regime including PCT at dominant heights of 2–5 m. Patterned area indicates land expectation values for a FBT system used in combination with integrated bundling (Paper IV).

4.5 Biorefinery product potentials (V)

The profitability estimates in study IV assume that prices are constant over time. However, prices are likely to change, mainly due to changes in supply and demand. According to Leskinen and Kangas (2001), the price of Finnish sawlogs is influenced by quality aspects and diversification of end-products, whereas pulpwood prices are considered to be dependent on the competiveness (i.e. fibre length) in comparison to fast-grown tropical hardwoods. In study V, the Swedish electricity price and wood fuel price changes between 1993 and 2011 were found to be correlated (Pearson correlation = 0.91). In addition, more than 90% of the respondents to the questions stated that the product value is affected by the electricity price. Higher future electricity prices are expected to encourage energy efficiency and a general move towards more renewable technologies (Anon. 2008b); thus, the incentives to invest in wood-based biorefineries may also increase. On average, electricity prices within OECD countries are expected to increase by 15% between 2011 and 2035 (Anon. 2012e). According to the relationship found in study V, Swedish wood fuel prices would increase by roughly 10% over the same period. Prices of wood fuel assortments are, to varying degrees, also affected by competition between assortments, by oil prices, by society's environmental concerns (Olsson 2012), and by production costs (Hillring 1997). As the situation stands at present, the price change in wood fuels is also dependent on the forest industry. Pulpwood and saw timber industries are needed to ensure profitability within the forest industry sector and, thus, to enable cost-efficient removal of fuel assortments. Surpluses of fuel assortments at saw mills are often sold to the pulp and energy sectors. A decreased production within the saw timber industry would, therefore, affect the available market stock. The pulp and paper industries are net consumers of wood fuels. Thus, when pulp and paper production increases, the demand for biofuels also increases and vice versa. Hence, future price development of wood fuels depends on a complex array of interacting factors which complicates projections and modelling.

Of the respondents answering the survey in study V, 95% believed that the value of woody biomass will increase within ten years. Investment potentials of biorefinery products were anticipated to be greater over a ten year period compared to a five year period, while the opposite was thought to be the case for pulp and paper. The respondents were in agreement that most products are very easily combined with existing production chains, which means that the wood industry may not need to undertake costly and time-consuming adaptations. The respondents listed the following main opportunities and threats to wood-based biorefineries (number of answers within brackets).

Opportunities
1. Increased demand for green products (10)
2. Higher oil and energy prices (6)
3. Increased use of policy instruments (4)
4. Accessible raw material (4)
5. Research and technical progress (3)
6. Rural economic growth (2)

Threats
1. High investment costs (7)
2. Uncertain political environment (7)
3. Competition for raw material (7)
4. Ecological risks (2)

This is in accordance with results from a survey presented by Näyhä and Pesonen (2012), in which the increasing price of oil was considered the greatest global incentive for forest biorefineries whereas collection, accessibility and competition for raw material were seen as significant challenges to the biorefinery business. Conrad et al. (2011) performed a survey in the south U.S., finding that wood-energy mills and traditional forest industry mills reported that they were currently not competing for raw material, but large scale competition was expected within 10 years.

In Sweden, the capacity to pay for wood chips has reached the same level as pulpwood and is approaching timber price levels (Figure 10). Currently, biofuel harvesting has resulted in rather uniform end-products with small variations in content. However, promising value-adding products mentioned by the respondents to the survey in study V could be grouped into five categories: transportation fuels; specialty cellulose; materials and plastics; solid fuels and specialty chemicals. The bark, branches, needles and cones of young pines contain substantial amounts of fatty acids and extractive content (Backlund 2013). Therefore, young pine forests could become of interest for several biorefinery products. If the raw materials were to be cost-efficiently divided into fine fractions and refined so that high-value products could also be added there might be effects on future assortment prices and profitability. Therefore, new criteria for assortment classification of wood that are directed at specific end-uses might also be needed. Identification and mapping of probable extraction levels of the largest commercial tree species at certain stand ages are also required if large-scale outtake to biorefineries is to be considered. A new, diverse, assortment system could influence the profits linked to management of young forests positively and encourage biomass thinning in young forests.

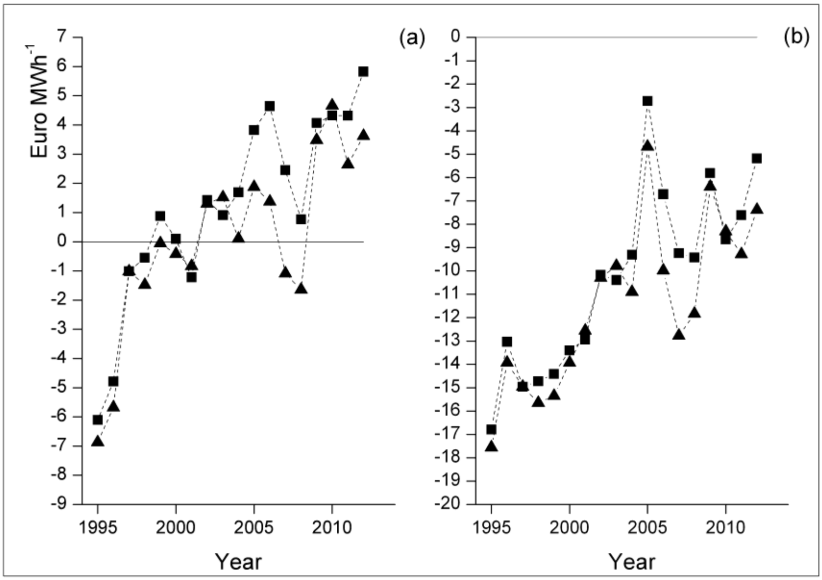

Figure 10. Yearly price development between 1995 and 2012 (Swedish market) of wood chips in relation to pulpwood (a) and timber (b) prices. Squares represent district heating wood chip prices and triangles represent industry wood chip prices. Solid lines denote when wood chips equal pulpwood and timber respectively. Sources: Swedish Energy Agency and Swedish Forest Agency (Paper V).

4.6 Conclusions, management implications and study limitations

The management of young pine forests has profound effects on the benefits that can be derived from the stand in the future. In Scots pine stands, the initial stand densities affect growth rates, biomass yields and the properties of the wood raw material obtained from late thinning and final felling operations. In this respect, the form and intensity of PCT and/or early thinnings are important tools that can be used to create a stand that is likely to fulfill specified goals. The results presented in this thesis suggest that the largest trees within a denser stand are able to make use of their hierarchical status and will continue to grow well regardless of the overall stand density. This indicates that it may be possible to combine a high early production of biomass with late harvests of large trees. The results presented suggest that the mean DBH of the 1000-2000 largest trees/ha should be considered when comparing different treatments and forest planning options because this variable provides information that is not obtained from the current standard silvicultural variables (e.g. mean stand DBH). This is because these large stems account for the majority of the future crop trees in a stand.

Scots pine and lodgepole pine stands with high stem numbers produces substantial amounts of biomass but need to be thinned at some point in time in order to avoid production losses due to damage and natural mortality. Simulations indicated that performing a schematic first biomass thinning in dense Scots pine stands is profitable when innovative harvest systems are used compared to conventional management regimes involving selective PCT. No significant negative effect of schematic harvest on the subsequent volume growth was revealed in evaluations of long-term field trials. Thus, schematic thinning may be useful for obtaining biomass from dense stands. Stemwood production was relatively independent of corridor PCT areas within the range of 60-80%. It therefore appears that there is a certain amount of flexibility with respect to geometrical pattern and harvest intensity in early corridor thinning. As a result, it should be possible to extract large quantities of biomass schematically provided that a relatively high stand density is retained. Harvest intensities of more than 60 and 40% of the total stem number at mean stand heights 6-7 and 8-9 m, respectively, are currently required in order to reach break-even financially when using boom-corridor thinning. Moreover, performing high intensity early thinnings in Scots pine stands seems to reduce the proportion of juvenile wood in mature trees. In the future, new end-uses of tree/wood raw material (e.g. in the production of biorefinery products) might require a diversification of the assortments assigned to young, dense pine forests. New criteria for classifying assortments may therefore be required, potentially based on information such as the fibre and chemical properties of the wood. Increases in the value of tree-biomass may encourage development of cost-effective harvesting systems, which could in turn change the harvest level required for cost-effective biomass thinning. All of these factors and possibilities should be considered in adaptive long-term silvicultural planning. Finally, there is a need for general thinning guidelines particularly for stands with higher stem numbers than would be left after conventional PCT. First biomass thinning operations need to be profitable in the long term. Therefore, the minimum harvest level can be determined by profitability. Profitability is, in turn, affected by stand characteristics such as average tree size and number of stems per hectare because these parameters influence operational costs. The upper removal limit in first biomass thinnings can typically be determined by considering the minimum sustainable site occupancy (e.g. leaf area index/basal area/stems per hectare) required to maintain a sustainable production of tree-biomass and stemwood given the resources available at the site in question (Figure 11).

This thesis is mainly based on data from 22 experimental sites and the results presented are of course only directly applicable to the species investigated. Due to the long time series and the frequent earlier inventories, the used field experiments provide relevant, and probably quite unique, information on young stand silviculture in the boreal forest zone. In studies I, II and IV, corridor harvesting was applied in a strictly schematic way, and the observed effects might not fully reflect those obtained after practical schematic harvesting using e.g. boom-corridor thinning. It is likely that further technical development will enable boom-corridor thinning to become a flexible working method that will facilitate cost-effective thinning without creating very strict geometric corridors. However, further evaluation of damage and mortality after corridor thinning in dense pine stands might be undertaken in order to acquire more information on the effects of the treatments considered in studies I and IV. Data on the effects of PCT in direct seeded lodgepole pine stands will be important for the future management of lodgepole pine. The results presented in study II represent initial results, and more long-term data will be required to obtain a more detailed understanding of treatment responses and facilitate major conclusions. The experimental sites used in study III were primarily chosen based on their well-documented stand history. Given the nature of the study, it would have been useful with more sample trees and detailed descriptions of the trees' status in the stand at different ages as this would have facilitated the interpretations of the results. Study IV addressed the economic aspects of implementing innovative harvest systems designed specifically for young, dense forests. Future analysis could potentially be extended to cover other stand densities, transportation costs and different levels of operational costs. Finally, due to the number of respondents to the survey in study V, its results might be interpreted carefully. On the other hand, those who took the time to answer the rather demanding questions delivered answers and comments that were considered to be highly relevant to the study's objectives. The study has thus contributed valuable information on perceptions of the potential future value of wood biomass components, which are likely to have influence on silviculture in the future.

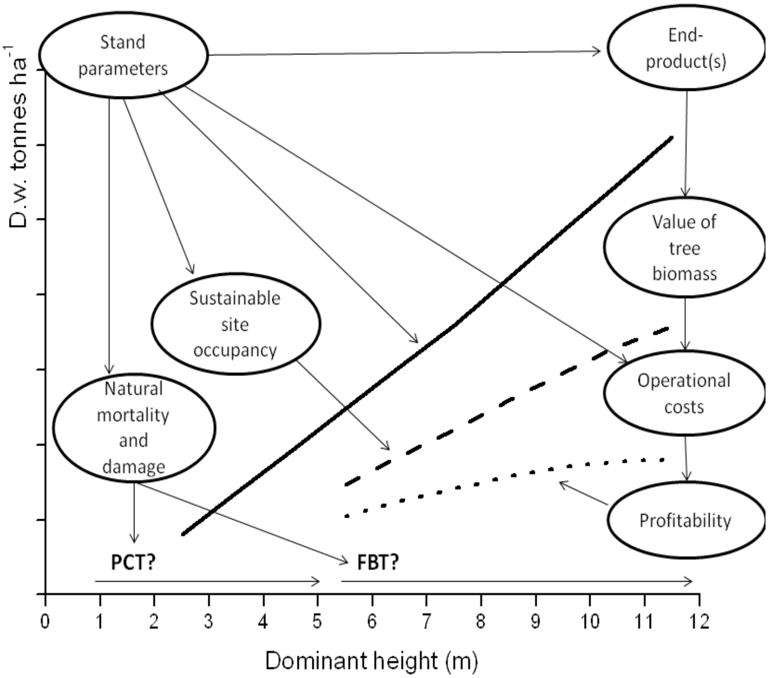

Figure 11. General parameters that influence the timing and intensity of silvicultural practices (PCT = pre-commercial thinning; FBT = first biomass thinning) in young, dense forests and in turn also the end-product(s) produced. The solid line illustrates total biomass production, the dashed line denotes maximum biomass removal in FBT as determined by ecological constraints and the dotted line illustrates the minimum removal level in order to achieve profitability in FBT.

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