Aspects of Precommercial Thinning in Heterogeneous Forests in Southern Sweden

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Doctoral thesis
Swedish University of Agricultural Sciences
Alnarp 2005

Acta Universitatis Agriculturae Sueciae
2005: 68

ISSN 1652-6880
ISBN 91-576-6967-8

Tryck: SLU Reproenheten, Alnarp 2005

Abstract

Fahlvik, N. 2005. Aspects of precommercial thinning in heterogeneous forests in southern Sweden. Doctor's dissertation.
ISSN 1652-6880, ISBN 91-576-6967-8.

The overall objective of the work underlying this thesis was to suggest and evaluate possible strategies for the tending of young heterogeneous stands of Norway spruce, Scots pine and birch in southern Sweden. Heterogeneity was defined as variation in species composition, height distribution and spatial arrangement of the trees.
The influence of stand density after precommercial thinning and timing of thinning on the diameter of the thickest branch was studied for naturally regenerated Scots pine. The branch diameter was found to decrease with increasing number of remaining stems after precommercial thinning. However, leaving very dense stands (> 3000 stems ha^{-1}) resulted only in a minor reduction of the branch diameter. Late precommercial thinning, compared to early, reduced the branch diameter. The influence of the precommercial thinning regime on the crown ratio (living crown length/tree height) was also analysed.
To be able to simulate the influence of different management options on the development of the young forest, single-tree growth models was developed for Scots pine, Norway spruce and birch. Height growth and diameter was estimated as a function of tree height, stand and site variables. Growth reduction due to competition was estimated using individual, distance independent indices as well as expressions of the overall stand density.
In the third study the influence of stand structure after precommercial thinning on the development of mixtures between Norway spruce and silver birch was simulated. The aim was to identify mixtures that allowed both species to develop well until the first commercial thinning. By leaving birches with an average height slightly greater than spruce at precommercial thinning, a large proportion of competitive birches were available at first commercial thinning, at the same time as the relative diameter distribution of spruce in the mixture was equal to that of a pure spruce stand of the same density. The height difference between the species as well as the species proportion had a decisive impact on volume production.
In the fourth study different precommercial thinning strategies were identified and applied to a heterogeneous stand including Scots pine, Norway spruce and birch. Stand development and economical returns over a rotation was estimated using a set of empirical models. The aim of the long-term strategies was: (i) a conifer dominated stand with focus on high production, (ii) a conifer dominated stand with focus on high timber quality, (iii) to preserve the heterogeneous stand structure, (iv) a mosaic pattern by tree species, (v) to reduce the precommercial thinning cost, without jeopardizing the future stand development. The difference in total volume production was found to be relatively small between the strategies. The lowest production was found for the strategies promoting species mixture at tree level (iii) and group level (iv). The net present value was highest for the strategy aiming at high production (ii) and lowest for the strategy aiming at preserved heterogeneity (iii). The minimal precommercial thinning (v) was a less profitable alternative, mainly because of an expensive first commercial thinning. Differences in timber quality were not considered in the simulations. The case study illustrates the possibilities for influencing the structure of a heterogeneous stand through precommercial thinning, as well as the limitations imposed by the initial stand structure.

Key words: *Betula* spp., branch diameter, cleaning, growth simulator, layering, mixed stand, *Picea abies*, *Pinus sylvestris*, spatial distribution, stand development, young stand.

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Contents

Appendix

Paper I-IV

The present thesis is based on the following papers, which will be referred to by their Roman numerals.

I. Fahlvik, N., Ekö, P.-M. & Pettersson, N. 2005. Influence of precommercial thinning grade on branch diameter and crown ratio in *Pinus sylvestris* in southern Sweden. (In press, Scandinavian Journal of Forest Research)

II. Fahlvik, N. & Nyström, K. Models for predicting single tree height increment and tree diameter in young stands in southern Sweden. (Submitted)

III. Fahlvik, N., Agestam, E., Nilsson, U. & Nyström, K. 2005. Simulating the influence of initial stand structure on the development of young mixtures of Norway spruce and birch. (In press, Forest Ecology and Management)

IV. Fahlvik, N., Ekö, P.-M. & Pettersson, N. Effects of different precommercial thinning strategies on a heterogeneous stand of Scots pine, Norway spruce and birch. (Manuscript.)

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Introduction

The possibility to influence the stand structure through thinning is regarded to be greatest in the young stand (*cf.* Pretzsch, 1999; Klang, 2000). It is therefore important to have clear goals and a sound knowledge of how precommercial thinning affects stand development. Understanding how current methods of precommercial thinning could be adapted to meet different objectives of forestry, *e.g.* economic, ecological and recreational, would be valuable. This is becoming increasingly important as the young forests of today have a more heterogeneous composition (*e.g.* Anon., 2002b; Anon., 2004a).

Precommercial thinning – application and research

Precommercial thinning became a standard silvicultural technique when the clear felling system was introduced on a broad scale in Sweden, in the middle of the twentieth century (Anon., 2002a). However, the history of precommercial thinning extends further back, and the importance of early thinnings has been emphasized in the literature for more than 150 years (*e.g.* af Ström, 1822). The current definition of precommercial thinning as "a tending removal of trees, without extraction of merchantable timber" has changed little over time, except that the definition now usually includes the extraction of biofuel (Anon., 2000c). The main objective of precommercial thinning has been to favour trees with desirable properties by removing individuals of inferior quality and poor growth potential (Björkman, 1877; Wahlgren, 1914; Juhlin-Dannerfelt, 1947; Anon., 1969).

Precommercial thinning in Swedish forestry

The most common motives for precommercial thinning today are to improve the growth of the remaining trees, to enhance mean timber quality and to influence the species composition of the stand (*e.g.* Anon., 1996; Anon., 2000a; Anon., 2000b). Furthermore, precommercially thinned stands are thought to be more vigorous than unthinned counterparts, with a better capacity to withstand damage, particularly damage due to snow breakages (*e.g.* Anon., 2000). Today, precommercial thinning has become an important tool in efforts to preserve and enhance the environmental and recreational value of forests (Anon., 2000a; Anon., 2000b).

Precommercial thinning is classified on the basis of the method used to select stems, the timing and the purpose of the thinning. First, a distinction is made between selective and geometric (schematic) thinning (Anon., 2000c). During selective thinning, the choice of stems is based on the properties and relative position of the individual stem, whereas in geometric thinning trees are removed in a defined pattern; rows, corridors etc. Selective precommercial thinning is the dominant method used in Sweden. Geometric thinning could be an option in highly mechanized systems (Bergkvist & Glöde, 2004) and is practiced in very dense natural regenerations of beech (Møller-Madsen, 2002). Precommercial thinning is carried out during the period between the sapling stage and the first commercial thinning. A special form of precommercial thinning, known as 'cleaning', involves a preparatory cut in dense regenerations with a mean height less than 1.3 m (Anon., 2001). This treatment is often limited to the thinning of dense groups of trees, together with the removal of wolf trees (dominant trees of poor quality, exerting heavy competition to neighboring threes) and unwanted fast-growing species.

Precommercial thinning is generally carried out in young forest areas, with a mean height greater than 1.3 m. Traditionally, precommercial thinning in Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) dominated stands is carried out as a single treatment when the stand is 2–3 m tall, leaving 2000–3000 stem ha^{-1} (*cf.* Anon., 2000a). The recommended stand density is usually somewhat higher for pine than for spruce and increases with increasing site fertility (Anon., 2000a). The main stems are selected from the healthiest stems of acceptable quality. Damaged trees and wolf trees are removed first. After careful selection of main stems, the usual objective is to achieve an even crown canopy and an even spatial distribution of trees (Anon., 2001).

Precommercial thinning in order to remove broad-leaved trees from coniferous stands and thinning aiming at high timber quality are usually recognized as two special cases of precommercial thinning. Removal of broad-leaves can involve total removal or point cleaning. In point cleaning, competing trees within a radius of 0.5 - 1 m around the main stems are removed. Subsequent adjustments are usually required as the stand develops and competition from neighbors increases (Karlsson *et al.*, 2002). Shelters are sometimes used in stands with spruce and naturally regenerated birch (*Betula* spp.) to protect the spruce trees from frost, to improve their quality, and to exploit the fast initial growth of birch (*e.g.* Johansson, 1992).

In successful regenerations with a high number of stems, *e.g.* natural regenerations of pine, the conditions are favorable for producing high quality timber. Precommercial thinning with the aim of increasing timber quality can be carried out in two steps in order to gradually release the competitive pressure on the main stems. The first is carried out as a ‘cleaning’, at a stand height of 1 m and the second at 4 - 5 m, when the number of stems is reduced to 2000 - 3000 stems ha^{-1} (*cf.* Anon., 2001). Precommercial thinning in broad-leaves is also often done in several steps (as described, for instance, by Ekö *et al.*, 1995; Anon., 2000a). Finally, cleaning or precommercial thinning is sometimes carried out in the understory shortly before the first commercial thinning. However, this should perhaps not be classified as precommercial thinning since it is only undertaken to facilitate the following operation.

Almost all precommercial thinning in Sweden is carried out motor-manually, using a brush saw. Attempts to mechanize precommercial thinning operations have so far failed, since the tested methods have only been profitable in a limited range of stand structures (Glöde & Bergkvist, 2003). However, research concerning methods of mechanized precommercial thinning is currently being undertaken (Bergkvist & Glöde, 2004; Ligné, 2004).

Research into traditional methods of precommercial thinning

Significant research concerning precommercial thinning began in the Nordic countries in the 1950s. To date, most of the research has been conducted in even-aged monocultures of Scots pine and Norway spruce. The main focus has been to examine the influence of different thinning regimes on stand development, especially in terms of volume growth and diameter distribution. The influence of precommercial thinning on quality-related properties has also been studied, but to a lesser extent. In the following discussion, the main results and conclusions from precommercial thinning experiments in pine and spruce dominated stands are reviewed.

In order to define thinning programs, pre-commercial thinning is usually described with respect to its intensity, timing and form. The intensity is often expressed as the number of stems remaining after thinning. The timing usually refers to the average tree height, while the form refers to the way in which stems are selected, *e.g.* removal of wolf trees, or the prioritized removal of certain tree species and/or trees of certain classes.

Several studies have found positive correlations between the number of stems after precommercial thinning and the development of stand volume (Vestjordet, 1977; Varmola, 1982; Fryk, 1984; Pettersson, 1993; Braastad & Tveite, 2000). Pettersson (1992) studied the effect of precommercial thinning resulting in 1000 - 8000 stems ha^{-1}. The total volume when the stand height reached 14 m was found to increase dramatically with increasing stocking levels at the lower densities. The volume in pine and spruce stands with 4000 stems ha^{-1} was 15 % and 25 % greater than in stands with 1000 stems ha^{-1}. However, the increase in volume leveled out at about 4000 stems ha^{-1}, *i.e.* additional stems had only a marginal influence on the volume. The potential volume growth is usually greater in unthinned stands than in thinned stands (*e.g.* Andersson, 1973). However, due to frequent damage occurring in unthinned stands, particularly snow breakage, experiments sometimes show the opposite result (*cf.* Andersson, 1974; Vestjordet, 1977). The timing of precommercial thinning also affects volume production. Thernström (1982) observed a considerably greater standing volume in pine stands 10 years after the establishment of an experiment when the thinning was undertaken at a mean height of 1.5 m compared to thinnings at 3 or 5 m. Varmola and Salminen (2004) studied thinnings at 3, 6 and 9 m height, and found no clear influence of timing on standing or total volumes. The greatest standing volume was, however, observed in the stand that had been thinned earliest (3 m).

The diameter growth of the remaining stems increases with increased thinning intensity (Haveraaen, 1960; Varmola, 1982; Pettersson, 1992; Hartig, 1999; Braastad & Tveite, 2000). The diameter growth after precommercial thinning has also been observed to increase with increasing tree diameter within a stand (Andersson, 1976; Braastad & Tveite, 2000). The positive correlation between mean diameter and thinning grade has been attributed to both the reduction in competition experienced by the remaining trees and the positive selection of more vigorous trees (Andersson, 1976; Pettersson, 1992; Varmola & Salminen, 2004).

With the current predominant use of wood as pulpwood and timber, the yield of merchantable wood is dependent on the tree dimensions. One of the most important features of precommercial thinning is, therefore, the possibility of adjusting the diameter distribution and, thus, the volume distribution. Unthinned stands and stands subject to low thinning grades will have a high total volume, but a large proportion of the volume will consist of small trees (Varmola, 1982; Pettersson, 1992). Hence, an increased thinning grade may result in an increased yield of merchantable wood although the total yield is reduced (*e.g.* Andersson, 1975). However, the optimum stand density after thinning in order to maximize the yield of merchantable wood is dependent on the minimum diameter requirements (Andersson, 1974; Varmola, 1982; Salminen & Varmola, 1990). With respect to the timing of precommercial thinning, it has been found that an early thinning increases the yield of merchantable wood at a given stand density (Andersson, 1974; Vestjordet, 1979; Varmola & Salminen, 2004).

The effect of precommercial thinning on height growth has not been as thoroughly studied as its influence on volume and diameter growth. Andersson (1976) studied the height increment of pine trees with the same height at the time of precommercial thinning and found no clear effect of thinning grade on height development. According to Varmola (1982) and Salminen & Varmola (1990), the dominant height of pine was not affected by the thinning grade in the stands they examined. Varmola & Salminen (2004) found no significant effect of thinning intensity on the mean height or the dominant height of pine stands 23 - 25 years after precommercial thinning. In a precommercial thinning experiment with spruce, leaving 820 - 2070 stem ha^{-1}, Braastad & Tveite (2000) reported that the increment of the dominant height was similar for all treatments; the assessment was made 28 years after thinning.

In both field experiments and practical forestry, the diameter of the branches is often used as an indicator of wood quality. In Scots pine, the diameter of the thickest branch on the lower part of the trunk has been found to be highly correlated with both visual timber grading and strength grading (Persson, 1976; Uusvaara, 1985). A number of studies have shown that the diameter of the thickest branch on the lower part of the stem increases with increasing precommercial thinning grade (Johansson *et al.*, 1992; Braastad & Tveite, 2000; Varmola & Salminen, 2004). For precommercial thinning to a given stand density, the future branch diameter can be reduced by carrying out the precommercial thinning at a later stage (Andersson, 1985a; Ruha & Varmola, 1997; Varmola & Salminen, 2004). Late thinning also reduces the effect of thinning grade on the thickness of the branches (Andersson, 1985b; Ruha & Varmola, 1997).

The development of the crown is another factor of importance for future wood quality. A fast natural debranching rate is favorable since it implies an early cessation of branch growth and an early start to the healing process. Ruha & Varmola (1997) and Braastad & Tveite (2000) reported a positive correlation between the height to the lower limit of the living crown and the stand density, 10 and 28 years, respectively, after precommercial thinning. Varmola & Salminen (2004) found the living crown limit of the 500 thickest trees ha^{-1} to be 16 % lower in pine stands with 1000 stems ha^{-1} compared to stands with 2200 stems ha^{-1}, 23 - 25 years after thinning.

Research in Sweden has also considered alternative precommercial thinning methods applied to stands other than pure conifer stands. In a number of experiments, different methods for gradually reducing the competition from secondary stems have been tested. Karlsson *et al.* (2002) compared point cleaning and conventional precommercial thinning, with respect to the development and quality of pine stems. The effect of topping (*i.e.* cutting the treetops of secondary stems) on height development and quality-related main stem properties has been studied in birch-dominated stands (Karlsson & Albrektsson, 2001; Fällman *et al.*, 2003; Ligné, 2004). Attempts to mechanize precommercial thinning have prompted studies on the biological effects of geometric precommercial thinning in pine and spruce stands (Eriksson, 1976b; Elfving, 1985; Pettersson, 1986a). Research concerning conventional precommercial thinning in stands other than monocultures of pine and spruce are rare in the Nordic countries. In an experiment on European beech (*Fagus sylvatica* L.), Ekö *et al.* (1995) studied the influence of precommercial thinning intensity on yield, diameter development and properties related to timber quality. A special type of structure that has been thoroughly examined is birch shelter over spruce (Andersson, 1985c; Tham, 1994; Mård, 1996; Bergqvist, 1999; Klang & Ekö, 1999; Johansson, 2001).

Ongoing changes in forestry practice

Forest policy, technology and economic factors have all influenced the frames and objectives of forestry (Anon., 2002a). Hence, the nature and intensity of precommercial thinning has varied over time as the conditions within which forestry operates have changed. The methods used in precommercial thinning must also be adapted to changes occurring with respect to regeneration practice and other factors influencing the structure of the young forest.

The high and sustainable production of valuable wood has been the prevailing forestry objective over a long period of time. The principle of sustainable wood production was specifically expressed for the first time in the Forest Act of 1948 (Enander, 2001). This Forest Act also implied that clear felling became the dominant silvicultural system and, hence, that precommercial thinning became a standard silvicultural measure (Anon., 2002a). Although the annually precommercially thinned area increased between 1950 and the end of the 1970s, the accumulated area of unthinned young stands increased steadily (Enander, 2003). In the Forest Act of 1979, precommercial thinning became mandatory, to ensure that future production goals were met (Ekelund & Hamilton, 2001). This Forest Act prescribed precommercial thinning in stands with densities above certain limits and included recommendations concerning the stand density after thinning (Anon., 1979). The Forest Act of 1979 was the most production-oriented act so far. In the present Forest Act, passed in 1994, environmental objectives are given equal importance to those related to timber production (Anon., 1994). The obligation to carry out precommercial thinning was dropped, allowing the use of alternative silvicultural methods (Enander, 2003).

In the 1980s, the concept of site adaptation was introduced as a response to standardized forestry. The concept implies that regeneration methods and silviculture should be adapted to natural variations in site conditions within stands (Lundmark, 1986). An important aspect of such adaptation is to promote the most suitable tree species composition for each site. The concept of site adaptation has been broadened in recent years to incorporate sustainable forestry, which takes a wide range of factors into consideration. The broadened concept has been implemented through the certification process, which incorporates many more environmental considerations than those prescribed in the Forest Act, *e.g.* the desirability of an increased mixture of broad-leaves in conifer stands (FSC, 1998; PEFC, 2000). Precommercial thinning is an important measure in attempts to meet the new goals.

The intensive precommercial thinning activity of the 1980s was followed by a dramatic decrease in the 1990s, due to factors such as deregulation prompted by the Forestry Act, lack of interest in long-term investments and a decline in the resources assigned to education and consultation (Anon., 2002a; Enander, 2003). In 2002, the annually precommercially thinned area in Sweden was 163 000 ha, compared to about 300 000 ha in the 1980s (Anon., 2004b). However, the area of forest at the sapling stage also decreased during this period (Anon., 2004a). The low levels of thinning activity have resulted in increasing proportions of young forest with an urgent need for precommercial thinning (ca. 900 000 ha) (Anon., 2002b). Precommercial thinnings have also changed in character, leaving denser stands and a greater proportion of broad-leaves than before (Pettersson & Bäcke, 1998; Anon., 2002b). Of a total productive forest area of 23 million ha, 19 % is classified as young forest, *i.e.* forests where the diameter at breast height of most stems is less than 10 cm and the average height is more than 1.3 m (Anon., 2002b). Spruce is the most common tree species (36 %) in terms of the growing stock with a diameter less than 10 cm at breast height, followed by birch (32 %) and pine (24 %) (Anon., 2004b). The extent of broad-leaved dominated stands and mixtures of broad-leaves and conifers have increased since the middle of the 1990s to about 40 % of the total area of young forests (Anon., 2002b). There is also a tendency to leave a higher number of broad-leaves as main stems in the regenerations (Anon., 2004a). In the season 2001/2002, 37 % of the regenerations were naturally regenerated and 60 % were planted (Anon., 2004b). The use of seed trees increased from about 10 % of the regenerated area in the mid-1980s to 40 % in 1995 and has then decreased to ca. 30 % in recent years (Anon., 2004a). In naturally regenerated stands, the main stems are generally more sparsely spaced and unevenly distributed than in planted stands (Anon., 2004a).

These new conditions will probably lead to a more heterogeneous structure in the young forests. At the same time, current forest policy has opened up opportunities for alternative silvicultural goals to be pursued and alternative silvicultural methods to be used. As mentioned above, most of the research related to precommercial thinning to date has focused on monocultures of pine and spruce. More knowledge is now needed about how precommercial thinning should be carried out in more diverse stand structures.

Heterogeneous young forest

Heterogeneity in this study refers to variability in stand structure parameters such as species distribution, tree height and the spatial distribution of the trees. Similarly, heterogeneous young forest refers to young stands with a pronounced divergence in the stand structure compared to typical even aged monocultures. However, the term heterogeneous does not necessarily exclude the possibility of achieving the same stand structure as in a monoculture after future thinnings. This thesis focus on heterogeneous young stands of pine, spruce and birch established after clear felling.

Establishment

A wide range of variables can cause heterogeneity in young forests, but factors influencing the plants during the regeneration period and sapling stage are likely to be the most important. Regeneration success depends on environmental conditions such as climate and site characteristics, *e.g.* soil moisture and nutrient availability (Kozlowski *et al.*, 1991). Thus, variations in site conditions might cause differences in regeneration success within a stand. When natural regeneration is used, the results are also dependent on the availability of seeds. Large variations in seed production have been found for many species by various authors (*e.g.* Hagner, 1962; Karlsson, 2001). Although the regeneration methods used over the vast majority of the forest land in Sweden are intended to favor pine and spruce, a large area of the young forests contains a significant proportion of broad-leaved trees, mostly birch (Anon., 2002b). Birch produces large numbers of seeds and it has efficient seed dispersal mechanisms (Karlsson, 2001). Birch seeds can, therefore, be distributed in large numbers over regeneration areas from trees left after cutting and from surrounding trees. Moreover, the frequent use of soil scarification techniques provides favorable conditions for the birch seeds to germinate (Fries, 1985). Since seedlings of different tree species differ in their responses to environmental changes, variations in the site conditions may alter the species distribution within a stand (Frivold, 1986; Beckage & Clark, 2003). Damage to the main tree species may also promote an admixture of other species and result in spatially irregular stands. The pine weevil (*Hylobius abietis* (L.)) poses a severe threat to newly planted conifers and can cause mortality rates of more than 80 % in unprotected plantations (Petersson, 2004). Locally, frost damage to spruce seedlings can be significant (Langvall, 2000). Browsing by moose (*Alces alces*) and roe deer (*Capreolus capreolus*) can cause severe damage to both seedlings and young trees (Näslund, 1986; Bergquist, 1998). Many of the damaging agents have a negative influence on height growth (Näslund, 1986), thus contributing to variations in height. Height differentiation is also likely to develop as a result of the different height growth rates of different species and inter-specific competition (Oliver & Larson, 1996).

Heterogeneity is not always the result of unsuccessful regeneration efforts. Some regeneration methods are deliberately intended to produce mixed stands. A common method used in Sweden to establish mixed coniferous stands is to combine planting of spruce with natural regeneration of pine under seed trees (see, for instance, Freij, 1990).

Classifying heterogeneous young forest

Classifying the heterogeneous forest is not straightforward because of the great variation in stand structure that can occur. However, a relevant description is necessary, both for scientific purposes and for practical forestry. Forestry research is dependent upon an objective description in order to guarantee comparability between treatments and to study the influence of stand structure on stand development. In practical forestry, information about the development and structure of the stand is needed for planning silvicultural operations and to identify possible silvicultural goals.

Traditional descriptions of even aged monocultures include stand averages of variables such as tree height, diameter, number of stems, basal area etc. The species distribution is often expressed as the relative basal area or as the relative number of stems of different species. In a homogeneous forest, this kind of information is usually sufficient to provide a clear description of the forest and allow appropriate silvicultural practices to be identified. However, conventional methods neglect the three-dimensional structure of heterogeneous stands. According to Pretzsch (1997), stand structure is probably the most important stand characteristics because of its impact on future stand development. The structure of the forest can be classified on the basis of three major characteristics: spatial distribution, species diversity and the variation in tree dimensions (Pommering, 2002).

In recent decades various indices have been used in scientific work to objectively quantify the different elements of heterogeneity (*e.g.* Kuuluvainen *et al.*, 1996; Pretzsch, 1999; Pommering *et al.*, 2000). The indices typically require data of a very high resolution and are usually applied at the single-tree level by describing the relationship between the subject tree and its neighbors (*e.g.* Clark & Evans, 1954; Ripley, 1977; Pielou, 1977). Even though these indices provide a detailed description of the stand structure, the type of detailed data required for this kind of sophisticated methods is not available in practical forestry situations. A more management-oriented description of the young stands, based on conventional inventory methods in combination with expressions of stand structure seems to be a more suitable approach to classification. Such a classification system could be based on the structure of the stand and/or criteria relevant for the management of the forest. A similar method was used by O'Hara & Oliver (1999) when developing a decision-making system for prioritizing objects at precommercial thinning in mixed stands. However, in Scandinavia little attention has been paid to classification systems involving stand structure (Leppäniemi *et al.*, 1998).

Development of heterogeneous forests

A number of studies have reported that birch mixtures have a negative influence on the growth of conifers in regenerations and young stands (*e.g.* Folkesson &

Bärring, 1982; Andersson, 1993). Andersson (1993) studied the early development of pine seedlings and found that birches taller than the pines, located closer than 1 m to them, had a severe negative impact. The competition from nearby birches has also been associated with beneficial effects by improving timber quality in conifer stands of low density (Hägg, 1989; Valkonen & Ruuska, 2003).

The most well documented case of precommercial thinning in heterogeneous stands is the use of birch shelters over spruce. Several studies have shown that a higher total volume production can be attained if a birch shelter is used compared to a pure monoculture of spruce (*e.g.* Mård, 1996; Bergqvist, 1998). Johansson (2001) found the total volume produced to be 24 % greater in stands where a birch shelter of 500 trees ha^{-1} was retained compared to stands where all birches had been removed at precommercial thinning, 13 - 15 years earlier. Tham (1988) found that a birch shelter of 800 stems ha^{-1}, kept until 25 years of age, results in the highest total production, although the production of spruce is slightly reduced compared to that of a pure spruce stand. Since the growth of Norway spruce is hampered by a dense birch shelter (Andersson, 1985c; Braathe, 1988), the birch is often removed or heavily thinned once it reaches a height of 10 - 15 m. Shelters of silver birch (*Betula pendula* Roth) usually have a higher volume production compared to shelters of downy birch (*Betula pubescens* Ehrh.) on normal sites (Tham, 1988; Valkonen & Valsta, 2001). The influence of birch shelters on quality-related properties of spruce was studied by Klang & Ekö (1999), who found that they significantly reduced both branch diameter and the frequency of defects associated with frost damage, *e.g.* spike knots and double tops.

The influence of mixtures on long-term production and stand development has been studied for different combinations of pine, spruce and birch. Comparisons of volume growth, many based on simulations, indicate that the total production over a rotation in mixed stands can equal that of pure conifer stands (Table 1). At mid-rotation, Jonsson (2001) found that the total volume production was 20 % lower in mixtures of pine and spruce than in a monoculture of pine. In another experiment with mixtures of pine and spruce, Lindén & Agestam (2002) studied the volume increment over a 20-year period, up to mid-rotation, and found that it was similar in the mixtures and the pure pine stands examined. Pukkala *et al.* (1994), who simulated the development of a mixed stand of pine and spruce, reported the volume to increase over a period of 10 years at mid-rotation to be a few percent higher in mixtures compared to the highest yielding monoculture.

In mixtures of birch and conifers, the high initial growth rate of birch might increase the volume growth in the early stage of the rotation (Mielikäinen, 1980; Frivold & Frank, 2002). However, since the volume production of birch is less durable than that of pine and spruce, a high proportion of birch usually results in reduced volume production in older stands (Mielikäinen, 1980; Jõgiste, 1998). Because of the different growth patterns of tree species, adjustments to the species distribution during the rotation are often recommended. For example, several studies recommend a progressive reduction in the birch component in mixtures with conifers, in order to maintain high productivity (Frivold, 1982; Mielikänen, 1985; Jõgiste, 1998; Lindén, 2003). The influence of species composition on volume production is also dependent on site fertility (see, for instance, Frivold & Frank, 2002). A common opinion is that the best conditions for mixtures are found at sites where the production of the species involved would be similar if they were grown in pure stands (Jonsson, 1962; Agestam, 1985).

Table 1. Comparison of total volume between mixed stands (V_{mix}) and pure conifer stands (V_{pure}) . In mixed conifer stands the total production of the highest yielding species is used as reference. In simulations the mixture with the highest volume is used for comparison

	Site index[b]			
Study	Pine	Spruce	Total age	V_{mix}/V_{pure} (%)
Pinus sylvestris – Picea abies				
Agestam (1985)[a]	20-24	22-27	80	99
Ekö (1985)[a]	16-28		70-80	100
Pinus sylvestris – Betula spp.				
Mielikäinen (1980) [a] (*B.Pendula*)	27-30		80	102
Agestam (1985) [a]	20-24		80	102
Ekö (1985) [a]	16-28		70-80	98
Frivold & Frank (2002)	14-20[b]		25-95[c]	No sign. diff.
Picea abies – Betula spp.				
Agestam (1985) [a]		22-27	80	99
Ekö (1985) [a]	16-28		70-80	98
Mielikäinen (1985) [a] (*B.Pendula*)		24-30	80-90	105
Mielikäinen (1985) [a] (*B.Pubescens*)		24-30	80-90	99
Frivold & Frank (2002)		17-23	15-45[c]	No sign. diff.

[a] Based on simulations

[b] H40 (dominant height at 40 years) is used in Frivold & Frank (2002), otherwise H100

[c] Average age at breast height for the conifer component in the included stands

Irregular spacing is likely to reduce the growth at stand level since it leads to sub-optimal exploitation of resources. Pretzsch (1995) simulated the effect of spatial distribution on basal area growth rates and found that an increased clustering resulted in reduced growth rates. Measures of irregularity have been used in basal area growth models to determine the effect of uneven spatial distribution (Eriksson, 1976a; Braastad, 1983). Eriksson (1976a) used the variance in basal area within a stand as a criterion for clustering and found that the growth reduction was greatest in less fertile spruce stands. The effect of irregularity after precommercial thinning has, to some extent, been investigated in comparisons between geometric and selective thinnings. Eriksson (1976b) developed competition models to study the effect of different precommercial thinning patterns on tree growth. The models, based on pine and spruce plots with an average height of 1.3 to 5.8 m, indicated that diameter growth was only affected by competitors within a 3 m radius of the subject tree, and no significant effect of one-side competition after precommercial thinning was found. Elfving (1985) studied line thinning in pine and spruce stands, using a strip width of 4.5 m, and reported a reduction in volume growth of 4 % five years after the thinning operation. In a line thinning experiment in naturally regenerated pine stands, with a strip width of 1.5 - 2.78 m, Pettersson (1986a) reported the volume growth to be reduced by up to 19 % after 10 years, in a study comparing combined geometric and selective methods with selective thinning. Both Elfving (1985) and Pettersson (1986a) concluded that the growth reduction was caused by an inferior stem selection process in the line-thinned stands. The effect of extraction roads on established spruce stands was studied by Eriksson (1994), who estimated that 5 m wide roads, with a distance, of 25 m reduced the volume growth by 8 % compared to selective thinning. Growth reduction due to extraction roads has also been reported by Isomäki & Niemistö (1990) in spruce stands and by Bucht (1981) in pine stands.

The effect of stratification on stand development is probably the least investigated aspect of heterogeneity. One reason for this might be the difficulty in isolating the influence of height distribution when comparing even and uneven stands, due to factors such as differences in age distribution and management. The results of Nordic investigations comparing even and uneven stands vary (*e.g.* Lundqvist, 1989; Andreassen, 1994; Lädhe *et al.*, 1994a; Lähde *et al.*, 1994b), and no general conclusion regarding differences in growth between them can be drawn. Most research has focused on differences between selection cutting systems and clear-cutting. Pettersson (1986b) reported results from an experiment in naturally regenerated pine, where unthinned plots were compared to plots in which dominant trees had been removed during precommercial thinning. In this experiment, where both site factors and age were controlled, only small differences in total volume were found between the treatments at the time of the first commercial thinning. However, the results were biased due to significant levels of mortality in the unthinned stands. Although the effect of stratification is not very clear in monocultures, stratification caused by differences in the growth rates of species in mixtures can have a major impact on stand development, as described above in the case of birch/spruce mixtures. However, due to differences in growth rates and shade-tolerance stratification may also result in the depletion of species, and thus change the species composition in mixtures (Oliver & Larson 1996).

Conclusively, potential volume growth during a rotation in mixed and pure stands depends on the species composition, the stages of development and the site conditions. Irregular spacing appears to have a negative influence on volume production. However, the degree of irregularity must be considered in relation to the stage of stand development. Stratification can be beneficial for the productivity of mixed stands but can also limit the possibilities to achieve long-term mixtures.

Precommercial thinning in heterogeneous forests

Planned management of the forest starts at the time of regeneration. In selecting a specific regeneration method, the forester determines the future stand structure. Precommercial thinning then becomes an important measure to achieve silvicultural goals. However, in many cases production of a heterogeneous forest is not the result of planned activity, but merely a consequence of factors that have not been controlled by the forester. In such cases, the decisions associated with precommercial thinning become more complex as the goals for future management must be revised in the light of the prevailing conditions. Whether the heterogeneity is intentional or not, a good understanding of the complex stand dynamics involved is needed to make appropriate decisions at precommercial thinning. Traditional research regarding the effect of precommercial thinning on stand development and timber quality constitutes an important basis for this understanding. However, additional information is required relating to the ways that the structure of heterogeneous forests can be controlled, as well as the long-term effects of different management options. One important factor driving trends towards increasing heterogeneity is the aim to increase biodiversity at all stages of the rotation. Thus, the options for creating sustainable mixtures of tree species are of special interest.

Objectives

The overall objective of the work underlying this thesis was to suggest and evaluate possible strategies for the tending of young heterogeneous stands of spruce, pine and birch in southern Sweden. Some essential intermediate goals were, therefore:

1. To expand our knowledge of the influence of precommercial thinning on quality-related properties of Scots pine in southern Sweden
2. To develop growth models for young stands of Scots pine, Norway spruce and birch in southern Sweden
3. To study the influence of stand structure after precommercial thinning on opportunities to create long-term mixed stands of Norway spruce and birch
4. To identify different precommercial thinning strategies in heterogeneous forests and study their effects, particularly with respect to stand development and economic return.

Summary of the papers

Paper I

The objective of this study was to examine the influence of precommercial thinning on properties related to timber quality in Scots pine. The study involved an evaluation of the influence of both stand density after precommercial thinning and stand height at the time of precommercial thinning on the diameter of the thickest branch and the crown ratio. In addition, the influence of the regeneration method on branch diameter was investigated.

The study was based on data from permanent sample plots situated in southern Sweden (57º–61º N). Plots established at 20 sites (115 plots in all) were examined, two of which had been sown, four had been planted and 14 were the result of natural regeneration. The plots were precommercially thinned to a density of 528 -

8000 stem ha^{-1} or were untreated. The average tree height after thinning was 1.2 - 8.3 m. Each plot was measured between two and six times, at intervals of about five years. The diameter at breast height of all trees was measured. Tree height, height to the first living branch and diameter of the thickest branch were measured on sample trees, randomly selected within each of the diameter classes. The measure of the thickest branch was taken 3 cm from the stem surface, 1-4 m above the ground when the future branch growth on this section of the stem was judged to be negligible. The crown ratio, *i.e.* the ratio between the vertical length of the living crown and tree height, was used as a measure of crown development. Plot-based averages of branch diameter and crown ratio representing all trees and the 500 thickest trees ha^{-1} were used as dependent variables in the analyses.

The average diameter of the thickest branch was 6.3 mm greater in the planted stands compared to the naturally regenerated stands. No significant difference was found between naturally regenerated and sown sites. The branch diameter increased with decreasing numbers of stems ha^{-1} after precommercila thinning, but the increase per unit reduction in stem number was minor at high stand densities (>3000 stems ha^{-1}). According to regression analysis, precommercial thinning to 1000 and 3000 stems ha^{-1} at a stand height of 3 m resulted in a thickest branch diameter (all trees) of 25 mm and 17 mm, respectively. The corresponding figures for the 500 thickest trees are 28 mm and 22 mm, respectively. Stand height at precommercial thinning significantly influenced the branch diameter; late thinning reduced the diameter of the thickest branch. Crown ratio decreased with increasing stand height, number of stems ha^{-1} and height at precommercial thinning.

Paper II

The aim of this study was to develop models for predicting height growth and diameter in young stands of Scots pine, Norway spruce and birch in southern Sweden. The growth model was intended to be applicable from the sapling stage up to an average height of about 11–13 m.

Models for single-tree height increment as well as static diameter-height relationships were based on data from permanent plots included in a nationwide survey of young stands. A subsample of plots situated in southern Sweden (<60º N) was selected for parameterization of the height models. The diameter-height models were based on data from plots with an average height > 6 m, distributed countrywide. Due to the hierarchical structure of the data (trees on plots within stands), the parameters were estimated using a mixed model approach. Separate models were developed for pine, spruce and birch. The prediction variable for height growth was the 5-year height increment of undamaged trees, and the static diameter-height relationship predicted the diameter at breast height (1.3 m). Height growth and diameter were modeled as functions of tree height, stand- and site properties. The competitive status of each tree was described using a distance-independent competition index. In addition, expressions of the overall density on the plot were included. The differences in height growth and diameter at a given height resulting from variations in site productivity were expressed using variables for temperature, climate and site factors.

Two independent sets of data were used for to validate the models; permanent pine and spruce plots within experimental sites and mixed stands of pine, spruce and birch on plots within the young stand survey. The validation indicated that the estimates of tree height and diameter were reliable up to an average height of at least 15 m. However, the height growth of birch was overestimated by 15 % on average. This was probably due to the frequent occurrence of damage to birch in the mixtures, which was not considered in the model. Spruce was slightly underestimated when validated against the experimental plots. This was assumed to be an effect of a more regular spacing in the experimental plots compared to the data used for parameterization.

Paper III

In this study, the development of mixtures of Norway spruce and Silver birch was simulated from the time of precommercial thinning until the first commercial thinning. The aim was to identify combinations of species that had potential to develop into long-term mixtures. The studied components of the stand structure were the average tree heights of spruce and birch as well as species distribution.

A growth simulator, based on the models described in paper II, was used to estimate the development of the different stand structures. The initial stand structure was generated by assigning tree heights according to a predicted Weibull distribution. Since the models referred to growth of undamaged trees, a model simulating damage and mortality was also included. The stands studied had an initial density of 2500 stem ha^{-1} and birch proportions of 0, 20, 40 or 60 %. The mixtures were also compared to monocultures of spruce with the same density as the spruce component of the mixed stands. The average height of spruce was set to 3 m, whereas the height of birch was varied from 1 to 6 m. The site conditions were chosen to represent typical conditions in southern Sweden. The results were compared at the time of the first commercial thinning (dominant height of spruce 13 m). However, in order to compare the volumes produced, a fixed simulation length of 15 years was used.

Since the study only concerned stand development up to the first commercial thinning, an expression for the capability of individual birches to survive and grow in the future stand was developed. The criteria for recognizing competitive birches were identified by examining variables that described vigorous birches in a survey study. For a birch to be competitive the ratio between tree height (m) and diameter at breast height (cm) had to be less than 1.25 and the height in relation to the dominant height (m) of spruce had to exceed 0.7.

The number of competitive birches at the time of the first commercial thinning increased with both increasing proportion and initial average height of birch. However, when the initial birch height exceeded 4 m, the increase leveled off. An initial birch height of at least 3.5 - 4 m was required in order for the birch to reach at least the same height as the spruce by the end of the simulation. The total volume of mixed stands was higher than in a pure spruce stand with 2500 stem ha^{-1}

only if the average height of birch was greater than 5 m at the start of the simulation. The volume after 15 years was always greater in the mixtures compared to a spruce stand with the same density as the spruce component of the mixture.

Given the conditions used in the study, it was concluded that leaving birches that are slightly taller than the spruce at the time of precommercial thinning will result in a high number of competitive birches at the time of first commercial thinning. If the initial height of birch is 0.5 - 1 m taller than the spruce, the mean diameter and the diameter distribution will be similar to that of a pure spruce stand with 2500 stems ha^{-1}.

Paper IV

The objective here was to study the influence of different precommercial thinning strategies when applied to a stand with great variations in the vertical and horizontal distribution of the trees and the species composition. Both stand development and economic returns were simulated over a rotation, starting at the time of precommercial thinning.

The study was based on data collected in a young stand within the Asa Experimental forest (57°08’ N 14°45’ E, altitude 190 m a.s.l). The stand was naturally regenerated, using seed trees of Scots pine and had undergone replacement planting with Norway spruce. The tree species involved were Scots pine, Norway spruce and birch (silver birch and downy birch), and their basal area weighted mean heights at the time of measurement were 3.8, 4.4 and 5.7 m, respectively. The height and diameter at breast height were measured for all trees within 38 sample plots (5 m radius). Five precommercial thinning strategies were defined and each plot was fictitiously thinned according to all the strategies. The following strategies were applied:

- *No precommercial thinning*
- *Minimal precommercial thinning.* This strategy was designed to reduce the precommercial thinning costs by concentrating on the purportedly most cost efficient measures. The operation was limited to include removal of the most extreme wolf trees and thinning of very dense clusters of trees.
- *Traditional precommercial thinning*. The objective of this strategy was, as far as possible, to create a homogeneous conifer-dominated stand. Main stems were selected from the most vigorous trees, in order to promote high productivity.
- *Precommercial thinning aiming at producing high quality timber.* In accordance with the traditional strategy, the aim here was to create a conifer-dominated stand. However, in this strategy the quality aspect was of greater importance than volume production. The selection of main stems was less affected by tree size than in the traditional strategy. Main stems of high quality pines were prioritized.

- *Retention of heterogeneity at the individual tree level.* The intention was to preserve the tree-wise heterogeneity in tree species composition and tree size that was present prior to thinning.

- *Retention of the species mixture at the stand level.* As an alternative to a tree species mixture, this strategy focused on separating the species into pure groups. The most dominant tree species within each area was prioritized at precommercial thinning.

In all strategies, wolf trees were removed.

The strategies were evaluated using a simulator incorporating existing models describing the growth of single trees, mortality and the yield of pulp wood and timber, together with current costs and prices. Thinning programs, based on the aims of the precommercial thinning strategies, were defined.

Choices during stem selection at precommercial thinning was limited if both the spatial distribution and the properties of the main stems (*i.e.* damage, timber quality etc.) were considered. On average, 75 % of the stems remaining after precommercial thinning to preserve a heterogeneous stand structure were also present after traditional thinning. Precommercial thinning to heterogeneous and mosaic stand structures resulted in the lowest total production at a stand age of 80 years; 6 - 7 % lower than the strategies favoring conifers. The highest production was achieved when precommercial thinning was neglected or carried out at a small extent. The greatest proportion of birch at final felling was achieved when aiming to preserve heterogeneity (13 % of the basal area). For the strategy intended to produce a mosaic stand structure, the proportion of birch at the time of the final felling was 8 %. The total net commercial return, at an interest rate of 3 %, was greatest for the traditional strategy and lowest after thinning to preserve heterogeneity. If precommercial thinning was either neglected or minimized there was a financial loss at the time of the first commercial thinning.

Discussion

Methods

Research concerning heterogeneous forests is complex due to the great possible variations in stand structure. Even if only a few stand parameters and management options are studied the number of possible combinations can be overwhelming. Field experiments can only deal with a limited range of this variation and are difficult to set up due to initial variation between plots of normal size, typically 0.1 - 1 ha. Consequently, a huge number of plots would be needed to obtain statistically significant results. It would also be difficult to generalize the results as there are no precise ways to describe heterogeneity. Furthermore, as no such arrays of plots are currently available they would have to be established, and there would be a long wait for the results. An alternative is to base analyses on simulations using models of growth and other variables. This type of analysis is therefore a central part of this thesis and was considered to be the only possible approach for the studies reported in Papers III and IV.

A great number of scenarios can be analyzed through simulations. Furthermore, stand and site conditions, and management, can be fully controlled. However, the reliability of the results from simulations is dependent on the ability of the models to estimate the stand development correctly. In both Papers III and IV a set of empirical models were used, including models for single-tree growth and mortality. These models are in most cases regression functions, where the dependent variable is estimated from easily measurable or classifiable tree -, stand - and site variables. However, this is also the general weakness of the empirical models, since the behavior of the models is highly dependent on the data used for parameterization (Peng 2000, Porté & Bartelink, 2002). Extrapolations and interpolations, which always generate uncertainties, are especially difficult to detect when studying mixed and heterogeneous stands (*cf.* Porté & Bartelink, 2002). Another related problem is how to specify the management in order to realistically mimic treatments carried out in practice, *e.g.* the choices of trees in thinnings, at the individual level. The studies in both Papers III and IV were based on simulations with empirical models, parameterized on large data sets from the HUGIN young stand survey (Elfving, 1982) and the Swedish NFI (Ranneby, 1987). The HUGIN data set, used for the parameterization of the growth models for young trees (Paper II), included about 900 plots in southern Sweden, whereas the growth model for older trees was based on data from 14 000 permanent plots from the NFI. The plots were systematically distributed throughout Sweden. Both materials covered a wide range of stand and site properties.

Accurate long-term forecasts of forest yield require reliable estimates of natural mortality (Fridman & Ståhl, 2001). However, mortality has been shown to be very difficult to predict due to its stochastic nature (Dobbertin & Biging, 1998). In Paper IV, the development of non-precommercially thinned stands was simulated. Non-precommercially thinned stands are regarded to be more prone to damages caused by for example snow, compared to thinned stands (Andersson, 1975). This kind of catastrophic damages is not considered in the mortality functions by Näslund (1986), used when forecasting the development of the young forest in this study.

Another general problem connected to long-term forecasting of growth and yield is the decreasing accuracy of the estimates with increasing prognosis length. This is partly due to that the forecast are made recursively, updating the independent variables every fifth year, but not reducing their impact on the forecast (Holm, 1981a). However, the main source of deviation from the true outcome is due to the future weather conditions (Holm, 1981b)

It should be recognised that in Paper IV all settings for the forecasts were the same, except for the treatments. Comparisons between forecasted treatments are considered to be more accurate than comparisons of forecasts to the true outcome.

This is due to that sources of errors often will have the same impact in different alternatives, thus disappearing when comparing them (Holm, 1981b).

Comparing data for the study stand in Paper IV and the specified treatments to the materials from which the growth and mortality models used for simulations were parameterized, the HUGIN survey of young forests and the NFI, it is judged that this stand types and treatments are well represented. The risk for extrapolations was considered to be greatest in Paper III, since the study was based on generated initial stand structures. The most critical cases were probably when the difference in height between birch and spruce was pronounced; especially when the birch was lower than spruce in the initial stand.

A source of uncertainty in the simulator used in Paper IV was the thinning algorithms. The thinning algorithms were based on criterions such as thinning grade (*i.e.* the proportions of basal area removed) and thinning ratio (*i.e.* the ratio between the mean diameter of the removed stems and the mean diameter of the stand before thinning). However, since the location of the trees was unknown at thinnings the algorithms did not consider the limitations at selection set by the spatial distribution of the stems. To make the thinnings more realistic, a random stem selection approach was applied in the simulations, making several forecasts for each plot. The average values were then used for further analysis.

Another feature of the investigations was the use of case studies. In Paper IV measurements from a single stand were used as the starting point for evaluating different precommercial thinning strategies. One of the major drawbacks with case studies is that it is difficult to generalize the results. Therefore it is essential that the studies focus on conditions commonly found in practical forestry. On the other, hand it is difficult in this kind of research to suggest alternative methods to the case study approach.

The initial stand structure and restrictions on tree selection in thinnings

The initial stand structure sets the scope to influence its development by selecting trees to remove in precommercial thinnings. Due to the greater variation in stand structure in a heterogeneous forest the options at precommercial thinning seem, *a priori*, to be greater than in a homogenous forest. One interesting issue is the degree of freedom to select trees, considering long-term silvicultural goals and normal silvicultural practices. In Paper IV it was concluded that if precommercial thinning is carried out to normal densities (approx. 2500 stems ha^{-1}) the freedom to select stems is quite limited due to considerations to spatial distribution of potential main stems and to individual tree properties, *e.g.* timber quality, damage etc. However, due to the varying conditions within a heterogeneous stand, the potential to influence the structure should also vary greatly. Thus, it might be possible to manipulate the composition at stand level, by exploiting the variations in site, tree and stand characteristics in different parts of the forest.

To further investigate the scope to influence the structure of a heterogeneous forest, a survey study was carried out within the stand described in Paper IV. In this study a subjective classification system was used to help identify long-term stand structures that met certain silvicultural objectives and could be attained, provided a suitable thinning program was applied. Subjective judgements of main stem properties and the spacing between them were the main criteria in the classification system. On systematically arranged plots with a radius of 10 m the extent to which different monocultures and mixtures could be created was assessed, following the rules for spacing between main stems and species composition presented in Fig. 1. Damage and social position (according to height) were the most important factors when judging the main stems. All potential main stems should also have good prospects to survive until the first commercial thinning and to yield at least pulpwood at that point. Overlapping between classes was allowed and, consequently, each area within a plot could belong to more than one class. In addition to the classification, the occurrence of gaps was estimated within each plot.

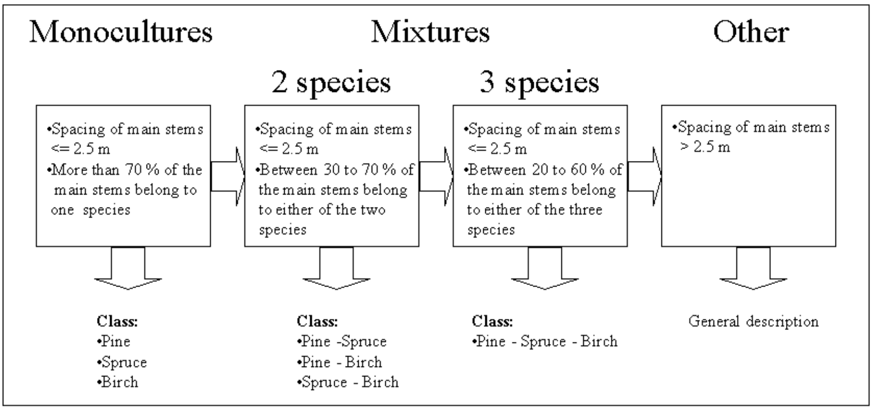

Fig. 1. General description of the classification system. The classification is based on the spacing of main stems and species distribution. The classified area can belong to more than one class.

The results from the classification were used to assess the consequences of three different precommercial thinning scenarios: thinning to maximize the area dominated by conifers, thinning to increase the area of tree-wise mixtures and thinning intended to generate a mosaic of clusters of pure species. In the first scenario monocultures of conifers had the highest priority followed by mixtures of conifers. In the scenario promoting tree-wise mixtures of species, mixtures including birch were prioritized and three-species mixtures were selected before two-species mixtures. In the last scenario groups with as few species as possible were selected and groups with birch were prioritized.

The analysis revealed that the criterion set for spacing between main stems was not fulfilled on 26 % of the stand area (Fig. 2). One of the main reasons for this proportion being so large was the frequent occurrence of gaps within the stand. On about 60 % of the plots there were at least three gaps with a minimum radius of 3 m, or five gaps with a minimum radius of 2 m, or both. Although the structure of the sparsely spaced parts varied greatly, the possibilities for selective thinning were very limited. These parts of the stand were therefore not considered when comparing the different precommercial thinning scenarios. A comparison of the scenarios for the remaining part of the stand showed that there were relatively small differences in the results between the thinning to increase the proportion of conifers and the thinning intended to create a mosaic patch-structure (Fig. 2). The most pronounced difference was the increased proportion of pure birch in the mosaic. The scenario with the objective to increase the tree-wise mixture resulted in the most diverse stand structure. In this scenario the proportion of mixtures of birch and conifers was increased at the expense of conifer monocultures. For the stand as a whole it was possible to choose between two or more distinct structures on 23 % of the area, whereas three or more structures could be created on 5 % of the area.

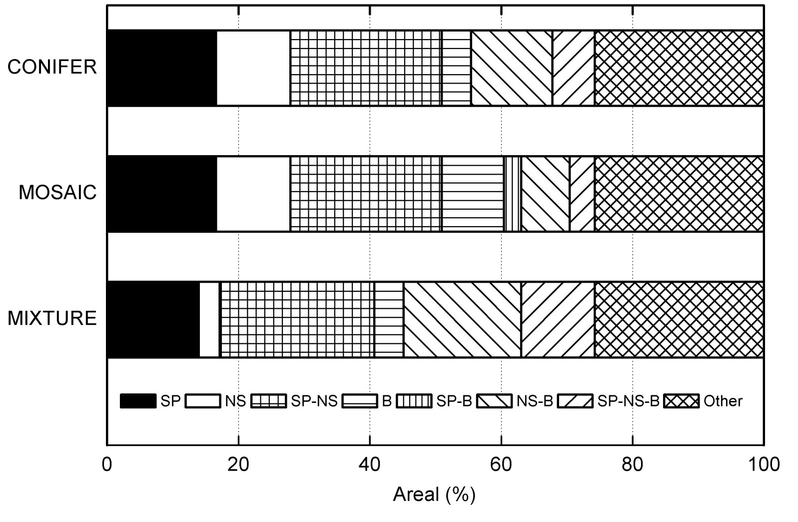

Fig 2. Distribution of species classes after three different precommercial thinning scenarios aiming at: conifer domination, mosaic patch-structure or tree-wise mixtures. (SP= Scots pine; NS= Norway spruce; B= Birch)

In conclusion, this example indicates that the stand structure of a heterogeneous forest can be changed in accordance to different strategies, but the scope for influencing the structure, in terms of species mixture, is limited if practical considerations are applied at precommercial thinning. Probably one of the most important factors determining the structure of the stand was the variation in site conditions. The establishment and growth potential of different tree species is to dependent on site conditions, which govern their relative competitiveness (Kozlowski *et al.*, 1991; Rackham, 1992; Oliver & Larson, 1996; Beckage & Clark, 2003). As expected, pine was dominant on dry sites, whereas spruce and birch dominated on moister parts of the studied stand (*cf.* Lundmark, 1986). Apart from the species distribution of the initial stand, the density of potential main stems also restricted tree selection at precommercial thinning. In addition to the frequent occurrence of gaps, some plots were subject to severe moose damage, particularly to pine and birch.

Managing heterogeneous forests

The knowledge derived from traditional precommercial thinning experiments is essential when managing heterogeneous forests as well as homogeneous forests. Due to the variation in stand structure, it is likely that large parts of a heterogeneous stand can be managed according to established practices. Thus, general principles regarding the influence of thinning grade and timing of thinning on stand development and tree properties will provide important guidance when making decisions for a heterogeneous forest. For example, in Paper I it was shown that quality-related tree properties, such as branch diameter, of pine depends on the stand density after precommercial thinning and timing of thinning. A conclusion of practical importance was that leaving very dense stands (> 3000 stems ha^{-1}) seemed to have only minor additional effects on branch diameter, and probably also on future timber quality. Findings like this can be used to set rules for precommercial thinning regarding variables such as stand density.

A subject of great importance in heterogeneous stands, for which traditional research gives little guidance, is how to manage mixtures of species. Due to differences in growth patterns and shade tolerance between species, the relationship between their respective heights is probably the most critical factor to consider at precommercial thinning in mixed stands. If stratification occurs among species, species in the lower height classes may be heavily suppressed, threatening the longevity of the mixture (Oliver & Larsson, 1996). The results presented in Paper III indicate that when spruce dominated initially in height, birch developed poorly and few birch trees were regarded as competitive at the first commercial thinning. Shade tolerant species like spruce have greater ability to survive in suppressed conditions (Oliver & Larsson, 1996). However, the growth of spruce was also severely hampered when dominated by birch, in accordance with earlier studies (*e.g.* Mård, 1996; Bergkvist, 1999). The main conclusion drawn in Paper III was that to create a sustainable mixture, in which both birch and spruce develop well, a single-storied mixture where the birch is slightly taller than the spruce after precommercial thinning seems to be most favorable. However, in reality the scope to influence the relative height of the species through precommercial thinning is limited, due to the initial parameters. Nevertheless, knowledge about suitable height relationships is important in order to identify structures in a heterogeneous stand with the potential for management as long-term mixtures. The findings in Paper III highlight the importance of timing when precommercial thinning is carried out in mixed stands, regardless of whether the goal is to maintain a mixture or for the stand to develop as a monoculture.

In the studies reported in Papers III and IV the precommercial thinning was carried out when the mean height of the conifers was 3-4 m. In heterogeneous stands, containing species with different growth rates, precommercial thinning at this height might be too late, if the aim is a specific silvicutural goal, i.e. the freedom to select trees is already quite limited. In Paper IV the mean height of birch exceeded that of pine and spruce. Spruce, as mentioned above, is able to survive beneath a shelter of birch, but its growth is hampered by the competition from the birches. Pine, on the other hand, does not have the same ability to withstand the shaded conditions if overgrown by birch (c.f. Folkesson & Bärring, 1982). Thus, if late precommercial thinnings are applied to stratified mixtures it might be necessary to base the future stand on the most dominant tree species and individuals. It is likely that the relatively late thinning in Paper IV contributed to the limited scope for selection within the studied stand. If precommercial thinning is carried out at an early stage, the number of potential main stems will be greater and the height difference between species can be adjusted. An early thinning can be carried out as a cleaning, focusing on dense groups and on wolf trees, or as an ordinary precommercial thinning. Another alternative is point cleaning, where the trees nearest to selected main stems are removed. A major drawback with early thinning is that there often is need for a subsequent thinning. Birch sprouts have a fast initial growth and can a few years after precommercial thinning cause severe competition to the coniferous main stems (Johansson, 1985; Andersson, 1985c). According to Andersson (1985c) the height of pine saplings must be about 1.5 m at the precommercial thinning to avoid them being overgrown by birch sprouts. The study refers to fertile sites for pine (site index 28 m). To use a several steps procedure requires careful planning, since omission to follow up the early thinning can be devastating for the future stand development (cf. Karlsson et al., 2002).

When planning precommercial thinning at stand level, a clear understanding of the long-term objective is essential. This is especially important in heterogeneous forests where the structural variation within stands must be considered (Paper IV) as well as the interaction between species (Paper III). At present, decisions are commonly based on data from forest plans describing the stands in terms of mean values of stem numbers, species distribution etc. However, these data have less utility in heterogeneous forests, since they may apply to a wide range of potential structures (Leikola, 1999). A description of higher resolution is needed. Therefore a classification system such at the one presented in Fig. 2 could be a suitable alternative, focusing on the silvicultural perspective. This method provides a realistic spectrum of the silvicultural options available at precommercial thinning, and is based on simple subjective judgments. This kind of subjective method, combined with estimates of tree height for different species, might offer an efficient way to acquire relevant information for decision-making. However, due to its subjectivity it is essential for the forest managers to have good knowledge to apply this approach in practice.

Strategies for the management of heterogeneous forests

In Paper IV, possible strategies for precommercial thinning in heterogeneous forests were identified. The strategies represent some obvious principles, but do not cover the whole range of options. Moreover, the height at precommercial thinning was case specific and might not be optimal for manipulating the stand structure. As mentioned above, an earlier thinning would probably have increased the possibility to select main stems more freely.

The simulations of stand development presented in Paper IV showed that if specific strategies were applied from precommercial thinning and onwards, the composition of a heterogeneous stand can be modified in accordance to different goals. The strategies affected both the volume production and economic results over a rotation.

Stand development

The estimated yield capacity of a homogenous spruce monoculture at the studied site in Paper IV, according to Hägglund & Lundmark (1987), was 25 % greater than the total volume production in the heterogeneous stand, if managed to promote high production. The estimated yield capacity refers to the production at optimal conditions, i.e. evenly spaced stands with negligible occurrence of damage. According to Hägglund & Lundmark (1987), spruce was the highest yielding tree species on all plots within the stand. Thus, the difference in volume production could partly be explained by the differences in species composition. Precommercial thinning strategies aiming at increasing the proportion of pine and birch were therefore likely to reduce the production of the studied stand. The strategies designed to retain either a heterogeneous structure through stem-wise mixture or a mosaic mixture resulted in the lowest production values; 6-7 % lower than for the strategy aiming at high production and conifer domination. The lower production in the heterogeneous stands compared to the potential growth of a pure spruce stand could also be due to the frequent occurrence of sparsely spaced areas in the heterogeneous stand.

In order to benefit from the different growth rates and niches of species and achieve mixture effects, the mixture must be fine-grained, *i.e.* a stem-wise mixture (Kelty, 1992). On the other hand, when precommercial thinning is carried out to a mosaic stand structure it is possible to concentrate each species at suitable sites (spots) (*cf.* Lundmark, 1986). No pronounced difference in volume production was evident between the stem-wise mixture and the mosaic patch-mixture in Paper IV. The strategies were, however, not fully comparable due to differences in species proportions. In general, the differences in total production between the different strategies studied in Paper IV were relatively small.

Preserving the heterogeneity through a stem-wise mixture probably offers a greater flexibility to adjust the stand structure at later thinnings compared to the mosaic mixture. In the mosaic mixture the species distribution is more or less fixed by the patch structure. However, the management of stem-wise mixtures is generally more demanding than the management of pure stands, due to their more complex stand structure and interactions between species at an individual level (Bartelink, 1999). Thus, a mosaic pattern could make silviculture simpler and increase the opportunities to retain certain species during a greater part of the rotation. A problem connected with the mosaic structure is the differences in the duration of volume production between tree species. It might not be optimal to use the same rotation length for a mosaic mixture including large patches of birch as for a conifer-dominated stand.

The positive effect of the removal of wolf trees was probably underestimated in Paper IV since neither the reduced competition experienced by the trees adjacent to the wolfs nor the supposed positive effect on the average quality of the stand could be correctly estimated in the simulations. Removal of wolf trees is likely to be more important in heterogeneous stands than in homogeneous forests due to the greater variation in height and the mixing of species with different shade-tolerance.

Economical returns

The strategies in Paper IV also affected the economic results over a rotation. For heterogeneous stands considerations other than economic return might be important, such as the desire to promote a greater proportion of broad-leaved tree species (see, for instance FSC, 1998). Nevertheless, economic evaluations make it possible to compare economic gains and losses compared to the supposed beneficial or detrimental properties of alternative approaches (*cf.* Lämås *et al.*, 1996)

The most economically profitable alternative in Paper IV was the traditional strategy, aiming at conifer domination with a high production. However, since the future timber quality could not be estimated in the simulations, evaluation of the different strategies was based on the assumption that no differences in timber quality would occur. The differences in net present value were due to variations in volume production, species distribution and tree dimensions. The lowest net present values at precommercial thinning were found for the strategies designed to preserve heterogeneity or a mosaic mixture. This was mainly due to their greater proportions of birch, which had relatively low production and low values of timber compared to pine and spruce. In Paper IV a fixed price lists for pulp wood and timber was used throughout the rotation. In an uncertain future wood market where the relative prices for different assortments fluctuate, a mixed stand may reduce the economical hazards (Lohmander, 1992; Carlsson, 1995).

When precommercial thinning was neglected or carried out at a small extent in the simulations (Paper IV) the net present value was reduced compared to the strategy aiming at high production. This was mainly caused by the high number of stems and the negative skewness of the diameter distribution. The economic results of these alternatives would probably have been even poorer if future timber quality had been considered. If precommercial thinning is neglected in dense stands it is usually necessary to base the future stand on the most dominant trees, which are often of poor quality (Pettersson, 2001; Cameron, 2002). Not carrying out precommercial thinning also reduces the scope to influence the species mixture. In the simulations described in Paper IV the effects of the thinning on the species distribution lasted for the whole rotation.

The management programs defined for each of the strategies were based on thinning guidelines for spruce, thus there were minor differences in the thinning grade and timing of thinning. It is likely that the aim of the strategies could have been achieved with greater volume production and economic returns if customised thinning programs had been applied. There is a need to increase the knowledge about the long-term management of heterogeneous forest in order to define such programs

Practical implications

- The timing of the precommercial thinning is more important in the heterogeneous stands than in the homogenous stands, and must be judged regarding the species composition and the long-term silvicultural goal.

- When making precommercial thinnings in heterogeneous stands at a normal, or higher average height (> 3m), the selection of trees could be quite restricted compared to what could be judged from a typical stand description. This statement implies that normal consideration is made to potential timber quality, tree class and the spatial distribution of main trees.

- To determine the density after precommercial thinning results from experiments in homogenous stands can be used as guidelines, for example when judging the effect on future timber quality. However, the species composition and the long-term silvicultural goal must also be considered.

- When precommercial thinning is carried out in mixtures including species of different growth patterns, the height difference between the species after thinning is crucial for the ability to create long-term mixtures.

- When determining the long-term goal for the heterogeneous stand a normal stand description gives only small guidance. Possible actions must be judged subjectively in the field from spot to spot, considering the overall strategy.

- The future timber assortments following different precommercial thinning strategies, with a consistent future thinning program might result in considerable differences in economical returns.

- Precommercial thinning including only the removal of wolf trees and the opening up of dense groups of trees seem not to be a profitable alternative due to an expensive first commercial thinning and the reduced possibility to influence the future assortments.

- Most of the statements made above should be regarded in the light of that there is a great variation among properties of heterogonous stands. It is therefore inevitable that treatments must be adapted to the current situation using general silvicultural experience and knowledge. (Which gives hope fore a future need of educated foresters.

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Acknowledgement

Firstly, I am very grateful to my supervisor Per Magnus Ekö for guiding me through this project. I thank my assistant supervisor Kenneth Nyström for all help and encouragement. I am also very grateful to my assistant supervisors Nils Pettersson and Eric Agestam for their support.

I want to thank Stefan Bergqvist at Asa Forest Research Station who helped me with the field works.

I also want thank Per Henrik Ekö, Anna Cederlund and Ingrid Cederlund for their contributions.

All colleges at the Southern Swedish Forest Research Centre have contributed to make the time as a PhD-student enjoyable and worthwhile. I appreciate the hospitality I have always experienced during my visits at Asa Forest Research Station.

At last, but not at least, I would like to tank my parents, my sister and my brother and his girlfriend for all support and encouragement.

The financial support for this thesis was granted by Brattåsstiftelsen and Rundvirkesfonden.