Influence of spacing and thinning on wood properties in conifer plantations

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Abstract

As reported in four appended papers (I-IV), effects of genotype (half-sib family) and initial spacing (I) or initial spacing (II) and various thinning methods (III & IV) on stands and properties of sawn-products were investigated in Scots pine (I & IV), lodgepole pine (II) and Norway spruce (III) stands in southern Sweden. Most of the analysed growth parameters were found to be affected by interaction between genotype and initial spacing, but the treatments had no significant interactive effects on most quality parameters (I). Very wide initial spacing (4x4 m, 625 trees/ha^{-1}) was found to negatively affect most growth and quality properties of lodgepole pine. Differences in effects of the density currently used in forestry (2500 trees/ha^{-1}) and a tested density (1100 trees/ha^{-1}, 3x3 m), were quite small, but increasing the spacing decreased frequencies of potential high quality trees. The results indicate that Scots pine and lodgepole pine have similar volume production rates and external quality traits (II). External properties of trees in the stands, particularly stem straightness and frequencies of quality defects (e.g. spike knots), were affected by the selection strategies applied in the thinning treatments. Thus, selection in thinnings should focus on these traits as they affect both the quality and grades of logs (III). The applied thinning treatments did not significantly influence board properties, such as basic density, Modulus of Elasticity and Knot Area Ratio. However, differences in these variables between outer and inner boards indicate that quality improvement might be connected to improvement in the growth of individual trees (IV).

In summary, use of improved planting material and wider than currently applied 2x2 m spacing in combination with selection of high quality trees might lead to production of higher quality timber. However, the scope for selection decreases with time and since the Scots pine boards from thinned stands and unthinned stands did not significantly differ the target traits and both objectives and market conditions must be carefully considered.

Keywords: Norway spruce, Scots pine, lodgepole pine, external wood quality, selection, thinning methods, spacing, thinning from above, thinning from below, thinning form, wood properties, wood characteristics.

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Dedication

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“Higher variability in wood characteristics exists within a single tree than among trees growing on the same site or between trees growing on different sites.”

Larson (1967)

Contents

List of Publications

This thesis is based on studies presented in the following papers, which are referred to by the corresponding Roman numerals in the text:

I Egbäck, S., Liziniewicz, M., Högberg, K.-A., Ekö, P.-M., Nilsson, U. (2012). Influence of progeny and initial stand density on growth and quality traits of 21 year old half-sib Scots pine (*Pinus sylvestris* L.). *Forest Ecology and Management*, 286, pp. 1-7.

II Liziniewicz, M., Ekö, P.-M., Agestam, E. (2012). Effect of spacing on 23-year-old lodgepole pine (*Pinus contorta* var. *latifolia*) in southern Sweden. *Scandinavian Journal of Forest Research* 27(4), pp. 361-371

III Liziniewicz, M., Ekö, P.-M. (2013). Effects of five tree-selection strategies when thinning spruce (*Picea abies* L. Karst) stands: Results from a field trail in southern Sweden. (manuscript).

IV Liziniewicz, M., Ekö, P.-M., Säll, H. (2014). The impact of thinning on the quality-determining properties of boards from 90 year-old Scots pine (*Pinus sylvestris* L.) stands in southern Sweden. (manuscript).

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Abbreviations

af	after thinning
bf	before thinning
CI	competition index
Dbh	Diameter at breast height
KAR	Knot area ratio
MOE	Modulus of elasticity
PCT	Pre-commercial thinning

1 Introduction

1.1 Background

Rapid economic changes in the Swedish forestry sector since the 1960s, especially increasing labour costs and decreasing timber prices, have forced rationalization of forest management practices to maintain economic efficiency, and thus competitiveness in the global arena. Two important initial measures to counteract increasing labour costs were reductions in planting densities and increasing mechanization of thinnings. In addition, foreign tree species and improved planting material have been used to increase timber production. Thus there are strong ongoing trends to regenerate stands with bred material, in wider than traditional spacings, and to use alternative tree species in attempts to increase timber production and thus maintain or even increase the profitability of forest stands in Sweden.

National breeding programs for the main tree species have been initiated and developed from the 1940's onwards (Danell *et al.*, 1993). Initially, the main goal for Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst) stands was to increase volume production including timber, although quality traits such as straightness and quality defects were also considered (Berlin *et al.*, 2010; Hannrup *et al.*, 2004; Haapanen *et al.*, 1997). Internal wood quality properties, such as basic density and fibre morphology, have also received attention, since they are highly inherited and strongly influence timber quality (Gerendiain *et al.*, 2008; Zobel & Jett, 1995; Kärkkäinen, 1984). Most of the planting material currently used in regenerations originates from seeds produced in seed orchards (Skogsstyrelsen, 2013b), which are believed to provide 10-25 % higher volume production rates than seeds from local, unbred sources (Hannerz, 1994; Rosvall *et al.*, 1994).

In the 1960's North-American lodgepole pine (*Pinus contorta* Dougl. var. *latifolia*) was introduced, mainly in the northern part of the country, with the aim of producing pulpwood in short rotations to counteract predicted pulpwood shortages (Elfving *et al.*, 2001). Currently lodgepole pine is the third most important coniferous species in Sweden and interest in it has increased in southern Sweden, although the Swedish Forestry Act (1994) restricts establishment of lodgepole pine in the region, as it grows 30-50% more rapidly than Scots pine (Elfving *et al.*, 2001). In addition, the pulpwood shortage was not as severe as expected and many stands have been left to produce sawn timber.

A possibly negative consequence of the use of new silvicultural and management techniques, breeding and new tree species in practical forestry is a reduction in wood quality (Bjorklund & Petersson, 1999; Klang & Ekö, 1999; Agestam *et al.*, 1998; Perstorper *et al.*, 1995; Ekö & Agestam, 1994; Persson, 1977; Persson, 1976). In the last two decades industrial demands for high quality timber have been constantly decreasing, due to strong competition in the timber and sawn goods markets, but the demand has been species-dependent.

Notably, quality substantially affects the prices obtained for Scots pine timber. However, there is currently no financial benefit for forest owners in growing high quality Norway spruce and the demand for high quality Scots pine is decreasing, although demand varies locally. Nevertheless, there is a strong correlation between the quality of raw material and quality of sawn products for end-use (Straze & Gorisek, 2011; Johansson, 1992), thus factors that affect quality cannot be neglected.

1.2 Stand management and its influence on wood quality

The scope to influence trees' quality changes as stands age, and are greatest during the establishment phase (Klang, 1999). In this phase, future timber quality may be influenced by the regeneration method, site preparation, choice of planting material, initial spacing, and planting quality. The growth environment is strongly influenced by the stand density, and both soil and climatic conditions, which influence the competition between trees and future quality traits. Thinning practices act both directly and indirectly on timber quality through their effects on the micro-environments of the trees' crown and roots (Zobel & van Buijtenen, 1989) and the selection of individuals with desired quality properties (Klang, 1999). Selection operations, such as thinnings (pre-commercial and commercial) influence stand density and are important tools for forest managers to influence growth and quality parameters after the establishment period (Fahlvik, 2005).

1.2.1 Planting material

The timber quality of trees in plantations might be enhanced by using improved planting material (Ekö & Agestam, 1994; Ståhl & Persson, 1988; Prescher & Ståhl, 1986; Persson, 1976), and as mentioned above ongoing Norway spruce, Scots pine and lodgepole pine breeding programs deliver seedlings that reportedly increase production rates by 10-25 % (Rosval, 2001; Rosvall *et al.*, 2001).Wood quality traits such as straightness, some branch properties and fibre characteristics have been considered in Swedish breeding programs as they are under high or moderate genetic control (Rosvall, 2011; Gort *et al.*, 2010; Zobel & Jett, 1995; Ekö & Agestam, 1994). Another important objective in the tree improvement programs is to identify genotypes that can provide superior yields across sites with wide ranges of environmental variables, notably site indexes and spacings (Rosvall, 2011; Zoebel & Talbert, 1984; Eriksson, 1980). However, knowledge about the interactive effects of genotypes and environmental factors is limited due to the lack of well-designed experiments in both Sweden and globally (Ye *et al.*, 2010; Zobel & Jett, 1995).

For Scots pine, Persson *et al.* (1995) found significant family x spacing interactions for total yield and tracheid length, but not for individual tree volume and basic density of wood. However, the material examined in the cited study was restricted to five local provenances. For Douglas fir (*Pseudotsuga menziesii* var. *menziesii*) Campbell *et al.* (1986) and Ye *et al.* (2010) found that these variables had significant interactive effects on growth parameters but not quality properties. Several studies have shown that variations in performance associated with genotypic variations depend on the competitive environment, e.g. spacing, thus a family that is highly productive at dense spacing will not necessarily be as productive at wider spacing (Aspinwall *et al.*, 2011; Gould *et al.*, 2011).

1.2.2 Regeneration method and initial spacing

Natural regeneration, or narrow spacing (of either sown or planted material), has been regarded as essential for producing timber with high quality parameters in both Scots pine and Norway spruce stands (Varmola *et al.*, 1998; Johansson & Persson, 1997; Ekö & Agestam, 1994; Johansson, 1993; Ekö & Agestam, 1990). Nevertheless, in Swedish conditions natural regeneration is used mainly for Scots pine. Natural regeneration has not yet been used for lodgepole pine, but in the future it might become common, since in its natural range natural regeneration is the main strategy for establishing stands of this species. Currently, lodgepole pine stands are established by planting or direct sowing. For Norway spruce, natural regeneration is seldom practised in Sweden due to the risk of wind damage. Furthermore, bred planting material with higher production capacity is preferred by forest owners. However, in Germany, Poland and both the Czech and Slovak Republics Norway spruce has been successfully naturally regenerated, especially in mountain areas (Röhrig *et al.*, 2006; Ulbrichova *et al.*, 2006; Jaworski, 1995). Natural regeneration of Norway spruce stands in Sweden is also possible (Nilsson *et al.*, 2002). As mentioned, high quality timber is not a focus of Norway spruce management. Thus, the required quality can be produced even with wide initial spacings.

The superior quality of Scots pine arising from natural regeneration or sowing is mainly due to abundant regeneration (>5000 stems per ha), which creates highly competitive growing conditions that enhance quality mainly by reducing branch diameter and reducing frequencies of crooked trees (Agestam *et al.*, 1998). Furthermore, the high densities of seedlings provide high selection possibilities. High establishment costs of planted stands and frequent severe damage by ungulates limit the establishment of Scots pine stands in Sweden. Thus, although high stem densities after natural regeneration substantially increase pre-commercial thinning (PCT) costs this method is preferred due to the lower risk of browsing damage. However, the method does not always provide sufficient regeneration. Frequent wind damage of shelterwood increases the general costs of the method. In Sweden, the proportion of naturally regenerated clear-cuts has been decreasing recently as planting other species, mainly Norway spruce, has been favoured (Skogsstyrelsen, 2013a).

Planting under a shelterwood has been found to positively affect the timber quality of Norway spruce trees (Klang & Ekö, 1999). Norway spruces planted under shelterwood reportedly have smaller average diameter at breast height (dbh), thinner branches, smaller annual ring widths and lower frequencies of stem defects than those planted in open conditions. However, birch shelterwoods have been found to have minor effects on Norway spruce wood and fibre properties (Bergqvist *et al.*, 2000; Bergqvist, 1998). For Scots pine, the duration of sheltering is positively correlated with future quality (Ekö & Agestam, 1994), and an important feature of regeneration under shelter, for both Scots pine and Norway spruce, is that frequencies of sharp bends and spike knots are reduced due to lower frost impacts (Klang & Ekö, 1999; Tegelmark, 1999; Örlander, 1993).

Of all traits monitored in various studies initial spacing reportedly has the strongest effects on dbh (Agestam *et al.*, 1998; Ekö & Agestam, 1994; Johansson, 1993; Johansson, 1992; Persson, 1977; Sjolte-Jorgensen, 1967). The faster diameter growth of trees planted at sparse spacings results in higher juvenile wood contents, wider annual rings and thicker branches that remain longer on the stem (Dinwoodie, 2000). However, growth rates are negatively correlated with basic density (Lowell *et al.*, 2012; Pape, 1999b; Kärkkäinen, 1984). Thus, trees growing at wider spacings and/or fertile sites have lower basic density than those growing at narrow spacings and/or poor sites. In Norway spruce stands, the pure effect of spacing is reportedly important for quality parameters such as crown height, natural pruning and branchiness, which are reflected in the knot contents of sawn materials produced from them (Johansson, 1997; Johansson, 1992).

Branch diameter in the first log is regarded as one of the most important determinants of log quality, especially for Scots pine logs (Anon, 2008b; Haapanen & Poykko, 1993). Trees planted at wide initial spacings are usually thicker, and thus have thicker branches than trees planted at narrow spacings or naturally regenerated trees (e.g. Johansson (1992); Persson (1977).

Initial spacings of 2200 – 3500 seedlings/ha^{-1} are currently used in Swedish coniferous plantations (with densities at the higher end of the range for Scots pine, and densities at the lower end for Norway spruce and lodgepole pine stands). However, for Scots pine, the current spacings result in inferior timber quality compared to naturally regenerated stands and stands planted at very high densities (Ekö & Agestam, 1994; Persson, 1976; Uusvaara, 1974). In addition, browsing damage affects the timber quality more strongly in sparse Scots pine plantations because of the low numbers of trees per unit area.

1.2.3 Thinning form

Stands that have been planted at a density of 2 500 stems/ha^{-1} and subjected to PCTs typically have 1 700 - 2 000 stems/ha^{-1} at the time of first commercial thinning. In practical forestry in Sweden, the first commercial thinnings in Scots pine and Norway spruce stands are recommended when they are 10-13 and 13-16 m tall, respectively. In commercial thinnings the selection of trees to cut plays an important role in future stand quality (Pretzsch, 2009; Pfister, 2007) and in many countries forest workers still mark trees to cut on the basis of careful observations. However, in Sweden essentially all thinning operations in coniferous plantations are fully mechanised without pre-selection.

The time of first thinning, thinning grade (heavy or light), thinning intensity (interval between thinnings) and thinning method (from above or below) all affect the growth and wood properties of trees by influencing their growth rates and the selection of trees with undesirable traits for removal. To date, scientific studies have generally focused on effects of thinning grade and intensity while less attention has been paid to effects of “selection” methods, especially with respect to timber quality.

In northern and central Europe, for many decades thinning from below has dominated in coniferous stands. However, diverse thinning methods have been described and/or applied, e.g. thinning from above, crown thinning, selective thinning and schematic thinning (Agestam, 2009; Pretzsch, 2009; Wallentin, 2007). In Sweden, thinning from above, in which the thickest trees and wolf trees are removed, has been discussed as an option to improve timber quality and increase early profits. Co-dominant and dominant trees remaining after thinning from above may have better timber quality in terms of thinner branches, narrower annual rings and higher timber density (Jäghagen & Lageson, 1996). Harvesting the thickest trees decreases machine costs and provides higher income from the thinning but might increase the rotation age (Lageson, 1997). Still in Sweden, majority of thinnings are made from below. However, due to consideration of other aspects than just dbh *i.e.* spatial distribution, economy, and stem quality, thinning is sometimes done from above.

In a comparison of the effects of thinning from below and above on external quality traits of Scots pine, Jäghagen and Lageson (1996) found that only straightness and frequencies of leaning trees differed significantly between the treatments, and thinning from above resulted in higher proportions of straight trees. Pape (1999a, 1999b, 1999c) compared effects of thinning regimes on various quality properties in Norway spruce, and found that thinning from above resulted in slightly higher basic density and lower ring width than thinning from below when the same percentage of basal area was removed. They detected no significant difference in the diameters of branches on the lower part of stems between stands thinned from above and below when the same basal area was left after thinning (Pape, 1999a). However, the stands analysed in the cited study had high initial densities (on average 3500 stems/ha^{-1}).

Delaying first thinning might improve the quality of first logs as it suppresses the diameter growth of branches, although they remain alive longer (Mäkinen, 1999a). However, from a selection perspective, the potential to use small diameter trees for high quality timber production decreases as trees become more suppressed (Oliver & Larson, 1996). In addition, delayed thinnings decrease the growth of individual trees and increase the risk of natural mortality and risk of wind damage (Agestam, 2009; Valinger *et al.*, 2006; Valinger & Pettersson, 1996). However, delayed thinnings have not been found to influence gross stem volume production of either Scots pine or Norway spruce trees (Nilsson *et al.*, 2010). Furthermore, in simulations of the consequences of shifts from even-aged to continuous cover Sitka spruce (*Picea sitchensis* (Bong.) Carr.) stands, Macdonald *et al.* (2010) found that regular selective thinning and crown thinning are likely to improve timber quality in comparison to the currently conventional thinning from below with unselective removal in strip roads.

There are also inter-species differences in timber production responses to thinning grade. In an extensive thinning and fertilisation experiment in Sweden significant losses of total production have been observed in thinned Scots pine stands, but not Norway spruce stands, with thinning grades up to 40% of stand basal area (Nilsson *et al.*, 2010; Eriksson & Karlsson, 1997). Both cited studies found that thinning from above had no significant effects on volume production, relative to thinning from below, in Scots pine stands, but tended to reduce production in Norway spruce stands. However, it increased net (merchantable timber) production in Norway spruce stands across the whole rotation, but not in Scots pine stands (Nilsson *et al.*, 2010). From a quality perspective, heavy thinnings removing more than 40% of basal area have been found to have negative effects on wood quality and increase risks of abiotic damages (Mäkinen & Isomaki, 2004).

Effects of the spatial distribution of remaining trees have also been considered in evaluations of thinnings. Notably, Pretzsch (1995) found that basal area increments were highest in stands with a regular tree distribution and negatively correlated with clumping. However, Karlsson *et al.* (2013) found no difference in effects on volume production of selective and corridor PCTs (with 57, 63, 73, 79 and 82% corridor areas) or between corridor thinnings and selective thinning (with 50% corridor areas and removal of 50% of basal area, respectively).

1.3 Selection criteria and their effects on wood quality traits

For many decades trees in thinnings were selected on the basis of careful observations of a single tree in Sweden. Traits reflecting growth potential (e.g. vitality, height and diameter), wood quality (e.g. straightness and spike knots), tree class (Kraft, 1884), and spatial position in relation to neighbouring trees were considered. Wood properties such as basic density, amounts of juvenile wood, grain angle, spiral grain, compression wood, knot area ratio (KAR) and modulus of elasticity (MOE) are important properties for timber quality. However, they cannot be observed in practical forestry. Nowadays, the only way to influence them is to use selected genetic material. Several specific correlations between external quality traits and the above mentioned wood quality indicators are well known and are described in the following sections.

Increasing labour costs and mechanisation of thinning operations made it unprofitable to manually select trees for cutting in thinnings in Sweden. However, it is still practised in some other European countries, e.g. Poland. Currently, the criteria for selecting trees to cut in mechanized thinnings must be easy to observe and strongly correlated with industrially valuable wood properties. For this reason, external quality properties such as tree class, dbh, straightness, branch diameter, number of branches, and stem defects can be used as selection criteria. However, the necessity of cutting strip roads in order for machines to work in stands is an additional factor that decreases selection possibilities in first thinnings.

1.3.1 Tree class in the stand

Initial variations among trees in planted stands depend on micro-site conditions, the genetic variability of planting material and environmental factors, both biotic and abiotic (Loubere *et al.*, 2004; Benjamin & Hardwick, 1986). When quantities of available resources are lower than requirements for optimal growth, competition between trees occurs (Pretzsch, 2009). One-sided competition, in which a thick tree solely suppresses growth of smaller neighbours, is considered the dominant type of competition on fertile and moderately fertile sites in the holarctic region (Oliver & Larson, 1996). However, two-sided competition (resulting in mutual reduction of two competitors' growth) has also been observed at poor sites with low site indices (Kenkel, 1988). The competition among trees results in differences in their dimensions (height, dbh, crown size) and reduces their vitality due to the accompanying changes in light conditions and nutrient availability. However, the competition among trees, and thus both their variability and stand traits, can be modulated by forest operations such as PCT and commercial thinnings (Loubere *et al.*, 2004; Stoyan & Penttinen, 2000).

The differentiation into size-classes occurs early in naturally regenerated (Borowski, 1974) or densely planted Scots pine stands (Nilsson & Albrektson, 1994; Nilsson, 1993). Just 6-7 years after planting Nilsson and Albrektson (1994) found significant differences in stem volume between trees that were to become dominant and suppressed. Similarly, Ruha *et al.* (1997) found that crown positions in naturally regenerated Scots pine stand were established at 5-10 years of age, when the saplings were 0.5-1.0 m tall, and was completed when trees reached heights of 1.5-2.0 m. The differentiation process has been shown to be mainly mediated by suppression of sub-dominant trees, which causes natural mortality in older stages. Shifts in social position have been rarely observed in planted Scots pine stands (Borowski, 1974). However, Bernadzki *et al.* (1980) reported that promotion of single trees from dominated groups upwards is species-dependent and more common among shade-tolerant species than among shade-sensitive species. The postulated reason for this is that suppressed individuals of light-demanding species lack the ability to restore their crowns sufficiently to increase their growth rates, thus possibilities for their promotion are very small. However, in the studies by Borowski (1974) and Bernadzki (1980), Kraft classification was used to describe biosocial positions of the trees and the authors provided no quantitative evidence for their findings. Nilsson and Albrektsson (1994) found indications that promoting suppressed Scots pines is possible but it must be done early in PCTs. The promotion of suppressed trees is regarded as a method to produce high quality timber as they usually have smaller contents of juvenile wood and thinner branches than dominants. Nilsson (1993) proposed a strategy for producing high quality timber by enhancing growth of both suppressed and dominating trees at the time of planting by mixing small and large seedlings.

In stands established by planting the variation in growth parameters, including height, among individual trees has been found to be small (Fahlvik, 2005). However, within a stand, the dominant and co-dominant trees usually have higher absolute growth rates and are more vital than dominated and suppressed trees. Thus, they have been favoured as potential crop trees (Abetz, 1974; Leibundgut, 1966). Faster growth results in wider annual growth rings and thus lower basic density (Pape, 1999b; Persson, 1972). Basic density is considered an important indicator of wood quality in many tree species, and other mechanical and physical properties can be derived from density parameters (Lukasek *et al.*, 2012; Molteberg & Hoibo, 2006; West, 2006; Jaakkola *et al.*, 2005; Macdonald & Hubert, 2002; Pape, 1999b; Johansson, 1993). However, Pape (1999a) found that basic density is only weakly affected by thinning methods. An implication of annual ring growth will be further discussed in the next section.

1.3.2 Tree diameter and annual ring width

It is cheaper to harvest trees with large diameters at breast height than those with smaller dimensions as harvesting costs are highly dependent on the average diameter of removed trees. In addition, large trees are more cost-effective to process than small trees (Steele, 1984). Thus, tree dimensions are important factors from both harvesting and timber-processing perspectives.

Peltola *et al.* (2002) found that the largest trees in studied Scots pine stands had the highest short-term absolute growth rates (measured 3 years after thinning) and post-thinning growth rates were strongly influenced by the thinning grade These findings indicate that the largest trees may have lower density than others due to wider annual rings. However, this was not confirmed by later findings that differences in annual ring width associated with different thinning grades did not lead to significant differences in wood density (Peltola *et al.*, 2007). Similarly, Pape (1999a) detected no significant associations between thinning programs and basic density, but did detect differences in densities between thin and thick trees due to differences in their growth rates. These authors, and Hannrup *et al.* (2000), also found that the relation between basic density and annual ring width can be described by a rotated J-shape curve, and that differences in differences between trees with annual rings wider than 1.5 mm are very low.

A negative correlation between annual ring width and basic density has been found in both Norway spruce (Pape (1999b); Johansson (1993); Kärkkäinen (1984)) and Scots pine (Kärenlampi & Riekkinen, 2004) stands. Thus, wide annual rings have negative effects on sawn-timber quality and yields of sawn and pulp products (Ståhl, 1988). There is huge variation in annual ring width, both within individual trees (with a tendency to decrease towards bark except in the juvenile phase) and among trees in stands (Pape, 1999a; Zobel & van Buijtenen, 1989). However, basic density generally increases from the pith towards the bark and decreases vertically from the butt to the top (Jyske *et al.*, 2008; Repola, 2006).

1.3.3 Straightness

The quality and yield of sawn wood are strongly influenced by the straightness of the tree (Gort *et al.*, 2010; Zobel & van Buijtenen, 1989; O'Brien, 1980) and lack of straightness and form stability, e.g. twists and warps of timber products, are factors that have contributed to the preference for steel in various commercial applications (Johansson *et al.*, 1994). Crooks affect the length of logs that can be cut from a tree, and thus the length and volume of sawn-products. They also reduce both yield and quality of pulp-products, but increase extraction and transportation costs. Thus, straightness is the most important quality measure in the current grading rules for Norway spruce saw logs (Anon, 2008b).

Furthermore, crooked, bent and leaning trees produce compression wood and increase deviations in grain angle via adaptive responses that reduce strain. The properties of compression wood are inferior to those of wood from straight trees (Macdonald & Hubert, 2002; Prescher & Ståhl, 1986). Notably, the presence of compression wood in logs increases frequencies of twists, springs and bows in sawn products as it profoundly affects all shrinkage parameters (Perstorper *et al.*, 2001), especially longitudinal shrinkage (Macdonald & Hubert, 2002). These defects may also cause the formation of oval stems, which can decrease yields of sawn timber. This is particularly important in the plywood industry since it decreases veneer yields (Kärkkäinen, 1978).

1.3.4 Branches

Branch diameter is regarded as a strong indicator of wood quality and has been used in log grading schemes in Scandinavia (Ikonen *et al.*, 2003; Mäkinen & Makela, 2003; Klang & Ekö, 1999; Ekö & Agestam, 1994; Persson, 1976). In Swedish measuring rules for Scots pine the dimensions of branches on saw logs are important criteria, but not for Norway spruce logs as the minimum acceptable diameter for their first quality class is just 60 mm (Anon, 2008b).

In even-age monocultures of coniferous species, including Scot pine (Persson (1977); Remröd (1976) and Norway spruce (Pfister (2007); Johansson (1992), branch diameter is strongly and positively correlated with dbh. Thus, large trees have thicker branches on the lower part of the bole than small trees. Persson (1972) found that basic wood density decreases with increasing branch diameter in Scots pine. In addition to dimensions, the number of branches, their positions on the stem and their angles relative to the stem all affect log quality (Björklund, 1997). These traits are influenced both by the growth environment (which affects the number of branches and their locations on stems) and genetic factors (which affect the branch angle, among other variables) (Hannrup *et al.*, 2000; Zobel & Jett, 1995). Increases in branch size and frequency increase harvesting and processing costs in thinnings (Macdonald & Hubert, 2002).

If a branch is alive the associated knot continues to grow except for a few years before the branch dies (Mäkinen, 1999b; Weslien, 1995). Thus, retention of branches on the stem results in increases in both the abundance and size of knots, which are important quality parameters for end users of wood products. Knots decrease the strength and stiffness of wood and its visual appearance (Gartner, 2005; Brazier, 1977) due to interruption of continuity and changes in the direction (angle) of wood fibres (Grace *et al.*, 1999). The quality of logs with respect to branch diameter has been found to be strongly correlated with the diameter of the largest knot and positively correlated with the number of knots in centrally sawn boards from young Scots pines (Högberg *et al.*, 2010). The distribution and positions of knots in sawn goods also affect quality (Green *et al.*, 1999). Dinwoodie (2000) found that a clustered distribution of knots has a more significant negative effect than an even distribution. Knots located at the top and bottom edges of a plank are more influential those located in a central part of a board. In the pulpwood industry, increases in both knot wood density and colour increase the costs of pulp processing (Macdonald & Hubert, 2002).

The reduction of strength associated with knots is caused by changes in fibre angles and interruption of wood continuity as growth rings of branches join growth rings of the stems (Green *et al.*, 1999; Raprager, 1939). Moreover, compression wood is formed at the base of branches via adaptive responses that increase support for them (Schultz, 1997). Both of these traits negatively affect wood quality, especially on strength and shrinkage parameters (Perstorper *et al.*, 2001).

1.3.5 Stem defects

Spike knots, double tops and sharp bends are common defects that decrease wood quality, sometimes sufficiently to make the material unsuitable for sawn products. These defects often result from leading shoot damage caused by various factors, e.g. browsing, frost or snow. Often, a double top will eventually become a spike knot since one of the tops will become apically dominant (Skogsencyklopedin, 2011; Zobel & Jett, 1995). Prescher and Ståhl (1986) found differences among Scots pine provenances in frequencies of spike knots, indicating that their formation is at least partially under genetic control. In Scots pine stands in Finland Huuskonen *et al.* (2008) observed more quality defects (crooks and branchiness) in the northern part of the country, indicating that a harsh climate may increase frequencies of stem damage. Spike knots at the bottom of stems will not make them completely unusable for saw logs, but they will reduce yields as shorter logs will be cut.

Spike knots, like all other knots, decrease the strength of sawn products, especially in combination with bark ingrowth (Dinwoodie, 2000; Ståhl *et al.*, 1990; Prescher & Ståhl, 1986). The presence of spike knots increases the knot area ratio (KAR) of final products, thereby impairing the strength of timber goods. The KAR can be defined as the area that knots occupy in a piece of wood relative to its surface area. Spike knots might be present on the stem for a long time as they are significantly thicker than ordinary branches. Thus, they may influence the natural pruning rate (Mäkinen & Colin, 1999).Thus, they were indicated as one of the factors which might influence the natural pruning rate (Mäkinen & Colin, 1999). As spike knots are usually the thickest knots they have the most significant influence on sawn wood strength (Dinwoodie, 2000).

2 Objectives

The overall objectives of the studies this thesis is based upon were to:

- Investigate possibilities for selection in coniferous (Scots pine, lodgepole pine and Norway spruce) stands at the time of first thinning.
- Evaluate effects of tested selection methods on future timber quality in Norway spruce stands.
- Evaluate effects of the common practise of thinning from below on the quality of sawn goods that can be obtained from Scots pine stands at the end of rotations.

These were main goals of the four studies presented Papers I-IV, designated Studies I-IV, respectively. Growth and external quality traits were the main focus in Studies I-III, while the quality of Scots pine sawn goods was the main focus in Study IV.

The specific goals addressed in the four studies are described below.

2.1 Paper I

The interactions between planting material and silvicultural treatments have not been widely studied, although use of improved planting material is currently increasing. The first objective of the study presented in this paper was to compare the growth and quality traits of trees in Scots pine stands established with seedlings of specific provenances and stands established as mixtures of various origins. The second objective was to compare the growth performance of trees of all included genetic origins growing at three different spacings.

2.2 Paper II

Interest in planting lodgepole pine has increased since it has been found to grow more rapidly than native Scots pine in the northern part of Sweden (Elfving *et al.*, 2001). However, its potential utility in southern Sweden has not been previously explored, due to legal restrictions on the establishment of lodgepole pine and a lack of experiments. However, there is growing interest in increasing timber production in southern Sweden and lodgepole pine is regarded as one option for meeting this objective. In addition, replacing Scots pine, which is highly browsed across the whole country, with lodgepole pine might reduce browsing damage. Thus, the growth and external quality characteristics of lodgepole pine cultivated at four spacings were analysed. The possibility to select crop trees to produce valuable sawn timber at rotation age under different spacing regimes was also evaluated.

2.3 Paper III

When mechanized thinning began to dominate in Swedish forestry in the late 1980's and early 1990's, selection strategies were adjusted to facilitate use of the machines. It has been assumed that this would have adverse effects on the retained trees' growth and quality, but this assumption has not been rigorously tested. Thus, the effects of different thinning methods were evaluated in this study to test the hypothesis that selection strategies focused on high quality trees might increase the timber quality of Norway spruce stands at the end of rotations.

2.4 Paper IV

Previously obtained data from long-term thinning experiments in Sweden indicate that the total volume production is lower in thinned than in unthinned Scots pine stands (Nilsson *et al.*, 2010). However, several studies have found that the average diameter of the 300 thickest trees per ha does not significantly differ between them (Nilsson, 2013, pers. comm.; Agestam, 2009). Thus, thinning operations may be justified in such stands in order to enhance wood quality. In a 90-year-old Scots pine stand examined in Study IV traces of the vast majority of external quality traits had already disappeared, thus they could not be observed. Hence, quality properties of boards from thinned and unthinned stands were analysed. The hypothesis that wood products from thinned stands would be superior to products from unthinned stands in terms of basic density, MOE and KAR was tested.

3 Methods and main results

This chapter provides a short overview of the methodology used in each of the four studies and the main results. More detailed descriptions of individual experiments and results are included in the corresponding papers. All the study plots were located in southern Sweden and are parts of a long-term experimental network (Figure 1). Generally, they were established as randomised blocks. At each experimental site the stand structure and external quality traits of trees were observed *e.g.* dbh, height, the diameter of the thickest branch, straightness and occurrence of quality defects (spike knots and double tops).

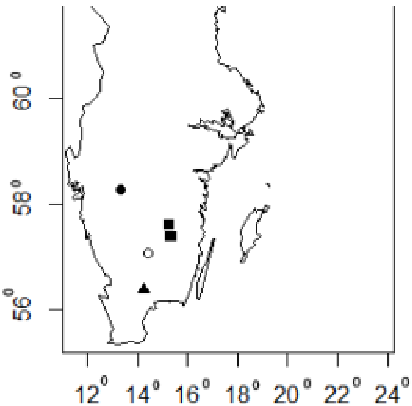

Figure 1. Locations of the studied forest sites. ● – Remningstorp (Paper II), ■ - Hässleby and Bockemålen (Paper II), ○ – Asa – two sites (Paper III) and ▲ – Veslarp (Paper IV).

3.1 Paper I

3.1.1 Materials and methods

The material for this study was collected at an experimental site established in 1990 in the Remningstorp Estate, located in the middle of southern Sweden (Figure 1).

The experiment was divided into two parts, referred to as B (block plots) and S (single-tree plots). Part B was laid out in a complete randomized block design with three blocks and ten plots 0.04 ha. Each plot was planted with 100 seedlings of a one half-sib family of Scots pine. Ten families were used in this part of the experiment, each planted in one plot per block.

The second part of the experiment (S) lacked a rigorous statistical design as treatments within it were not randomized, probably due to limited amounts of available space in the stand at the establishment time (see Figure 1 in Paper I). Three spacings (1 x 1 m, 2 x 2 m and 3 x 3 m) were each assigned to four plots, and in each plot 10 half-sib seedlings of 30 different Scots pine families were randomly planted. Thus, there were 300 seedlings per plot in total. All the families included in the first part of the experiment (B) were also included in the second part (S).

Trees were measured at ages of 7, 9 and 21 years. At 7 and 9 years, the height (HT) of all trees was recorded. At 21 years the dbh (DBH) of all trees in both experiments was measured, and the height of randomly chosen trees belonging to the 10 families growing in the B part of the experiment. Until the last inventory, the experimental stands were subjected to PCTs with the aim of removing naturally regenerated trees. The following traits related to timber quality were measured and assessed at 21 years: the thickest branch diameter (BR), branch angle (ANG), overall quality (QL), straightness (STR), and frequencies of spike knots (SK) and double tops (DT). The volume of individual trees (VOL) thinner and thicker than 50 mm were calculated using functions presented by Andersson (1954) and Brandel (1990), respectively. In the following section growth and quality traits are indicated using the abbreviations in parentheses and the age of the trees when the experiment was inventoried. A mixed effect model was used to assess effects of half-sibs, spacing and their interaction on the measured variables.

3.1.2 Results

There were significant interactions between Scots pine progenies and initial spacing at all ages for the growth traits ($p<0.05$), but not quality traits except spike knots ($p<0.05$) (Table 1). Differences between spacing were significant for all growth parameters ($p<0.05$) and for all quality values except overall quality and straightness. Trees spaced at 2 m were tallest at all ages, followed by trees at 1 m spacing. Trees in 3 x 3 m spacing were the lowest at all ages and significantly shorter than trees in 2x2 m spacing. At 21 years there were significant differences between all spacings in diameter and volume production. Trees in the 3 x 3 m spacing were the thickest and trees in 1x1 m spacing were the smallest. Trees in 1 x 1 m spacing had the smallest branch diameter at breast height and the lowest frequencies of defects (spike knots and double tops). Significant differences between the families were detected for all quantitative traits ($p<0.001$) as well as for branch angle ($p<0.05$) and occurrence of spike knots ($p<0.05$).

Table 1. *Significance of sources of variation in indicated traits according to analysis of variance based on data from individual trees.*

Source of variation	df	p-value				
		HT7	HT9	HT21	DBH21	VOL21
Spacing (S)	2	0.0497	0.0261	0.0171	<.0001	<.0001
Family (F)	29	<.0001	<.0001	<.0001	<.0001	<.0001
S x F	58	0.0044	0.0002	0.0425	0.0426	0.0437

	df	BR21	ANG21	QL21	STR21	SK21		df	DT21
Spacing (S)	2	<.0001	<.0001	0.0660	0.2689	0.0036	Spacing (S)	2	0.0178
Family (F)	9	0.9445	0.0019	0.2339	0.0790	0.0134	Family (F)	8	0.4747
S x F	18	0.8584	0.1631	0.1927	0.2813	0.0131	S x F	8	0.2728

Significant differences ($p<0.05$) between spacings were found for all growth traits. Among analysed quality traits, there were significant between-spacing differences for the thickest branch diameter, branch angle, occurrence of spike knots and occurrence of double tops (section 4.1).

3.2 Paper II

3.2.1 Materials and methods

An experiment designed to assess effects of thinnings of lodgepole pine stands was established in two stands of the species (designated Hässleby and Bockemålen, close to the town of Mariannelund, southern Sweden; Figure 1) in

1987. The tested spacings were 1.41 x 1.41 m, 2 x 2 m, 3 x 3 m and 4 x 4 m. There were two blocks at each experimental site, and each spacing was replicated once within each block. In addition to the original design, in one of the blocks at each experimental site, an additional plot was planted with Scots pine of the same age at 2 x 2 m spacing. These plots were not fully included in the analysis, but they gave important indications of possible differences in responses of the two species.

Growth data were collected in autumn 2007 from the Hässleby site and in autumn 2009 from the Bockemålen site. The stands were 23 years old at the time of evaluation. The diameter of all trees and the height of randomly chosen sample trees were recorded (Karlsson, 1998). The traits related to timber quality were measured and assessed in spring 2010.

Reductions in volume production and quality with increasing initial spacing were anticipated. A mixed model was used to evaluate the influence of spacing on growth and quality characteristics.

3.2.2 Results

The average dbh was similar at the two experimental sites, and significantly greater in the plots with the widest spacing 3.0-4.0 cm than in those with the narrowest spacing (Table 2). Frequencies of trees in small diameter classes were higher in the plots with narrow spacings, while frequencies of trees with large diameters were higher at wide spacings. Volume production per hectare decreased with increasing spacing and there were significant differences in both volume production ($p=0.003$) and average tree volume ($p=0.007$) (Table 2). Volume production was lower at wide spacings (on average 10% to almost 70% lower at 2 x 2 m and 4 x 4 m, respectively) than at the closest spacing (1.41 x 1.41 m). There were negligible differences in volume production between lodgepole pine and Scots pine trees growing at 2 x 2 m spacing in the adjacent plots.

Table 2. *Mean values of measured variables of 21-year-old lodgepole pine in the spacing experiments at Hässleby and Bockemålen.*

Spacing	Mean height (m)	Top height (m)	Diameter[1] (cm)	Volume (m^3/ha)	Volume (dm^3/tree)	Branch diameter (mm)	Straightness[2] (%)	Trees without defects (%)	High quality trees[3] (%)	Spike knots[4] (%)
1.41	9.2[a]	10.1[a]	9.8[a]	118[a]	40[a]	13.4[a]	89[a]	46[a]	69[a]	6.4[a]
2.00	8.8[a, b]	9.9[a]	11.4[b]	99[a]	52[a, b]	18.1[a, b]	83[a]	27[a]	43[a, b]	8.4[a]
2.83	8.8[a, b]	9.9[a, b]	12.1[b, c]	69[a, b]	60[b]	19.9[b]	85[a]	31[a]	43[a, b]	11.2[a, b]
4.00	8.1[b]	8.9[b]	13.4[c]	32[b]	66[b]	27.9[c]	78[a]	26[a]	17[b]	17.1[b]

Note: Values with the same superscript letter do not significantly differ at the 5% probability level.
[1] - diameter at breast height
[2] – Percentage of straight trees
[3] – Percentage of high quality trees (class 1)
[4] – Percentage of spike knots on the upper part of the stem (> 4 m)

The mean branch diameter significantly increased with increasing spacing ($p<0.001$), with a mean difference of 14 mm between the widest and narrowest spacings (Table 2). There were no significant differences in this respect between the two narrowest spacings: 1.41 x 1.41 and 2 x 2 m (Table 2). The mean diameter of the thickest branch in the three whorls closest to breast height was positively correlated with dbh, and significantly greater at the widest spacing than at the other spacings (Figure 2).

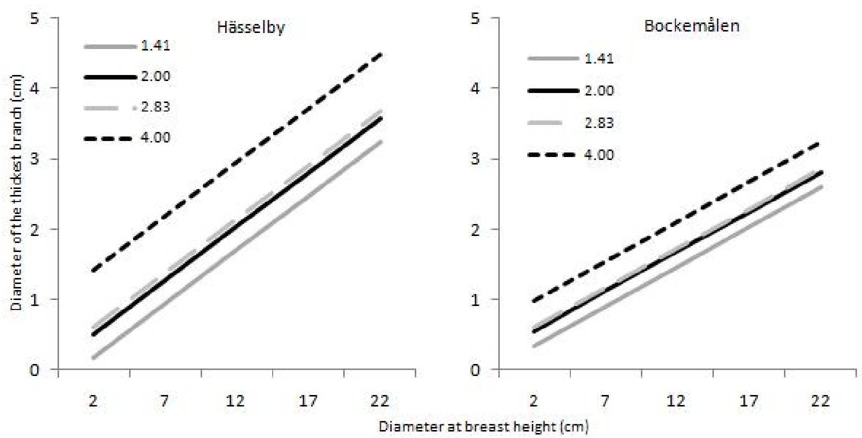

Figure 2. Relationship between dbh and diameter of the thickest branch in the three whorls closest to breast height.

The average proportion of straight trees did not differ significantly between the spacings (Table 2). On average, in each spacing almost 80% of trees were straight. Spike knots were the most common defects and 42% of dominant and co-dominant trees had at least one spike knot on the stem. Generally, frequencies of spike knots increased with increasing spacing.

3.3 Paper III

3.3.1 Materials and methods

A thinning experiment including five thinning strategies was established in 1989 in two Norway spruce stands, 32 and 31 years old, designated Taberg and Sandhage, respectively, located at Asa Research Park (Figure 1). The stands were established at an initial density of 2 500 seedlings/ha^{-1} with 4 year-old bare-root seedlings.

There were six plots within each stand: an unthinned control plot and five subjected to the following thinning treatments: thinning to retain high quality trees (HQ), thinning to retain low quality trees (LQ), thinning from above (A), thinning from below (B) and thinning aiming to achieve an even spatial distribution (S). Trees in these plots have been measured on three occasions. Before first commercial thinning the dbh and quality traits of all trees were observed, and the height of randomly chosen sample trees was measured. The second measurements were done in 1999 just before the second thinning, following the same procedure as in the first measurements, except that there were no quality observations. At the third inventory in 2011, diameter and quality traits (straightness, occurrence of quality defects and natural pruning rates) of all trees were measured or judged. The height of randomly selected sample trees was also measured.

Based on quality measurements at the time of first commercial thinning, a quality index for all trees was calculated to select trees for cutting in the HQ and LQ plots. The index considered, in order of importance: spatial distribution within stands, tree class, crookedness, stem defects, diameter of the thickest branch and branchiness (average number of branches in the three whorls closest to breast height divided by the distance between whorls. In the HQ and LQ treatments trees with high and low quality indices, respectively, were preferentially retained (within the spatial constraints). The basal area before thinning differed between plots within the stands, but was reduced to the same level after thinning: 22 and 25m^2/ha^{-1} at Taberg and Sandhage, respectively.

3.3.2 Results

The applied thinning treatments influenced subsequent changes in the dbh distribution at both locations. The A, LQ and S treatments favoured small diameter trees while HQ and B treatments favoured thick trees (Figure 3 in Paper III). This resulted in higher stem densities in A, LQ and S plots. However, the average dbh did not differ significantly between treatments. Volume production was not significantly affected by the thinning treatments during the analysed periods (Figure 3).

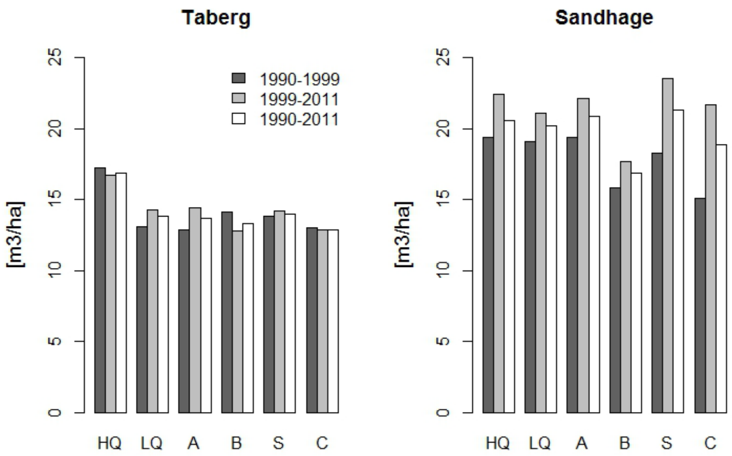

Figure 3. *Mean annual increments (MAI) in the three analysed periods.*

The distribution of trees in the straightness classes did not differ significantly before the first thinning (p=0.9664). However, only 1% of trees in the S plots at Taberg were regarded as straight (Figure 4). After two thinnings the differences were also insignificant but the variation between treatments was higher (p=0.0757). On average the HQ and LQ treatments resulted in the highest and lowest proportions of straight trees (> 80% and ca. 50%, respectively) at both experimental locations. The proportion of severely crooked trees was negligible after two thinnings, less than 5% under all treatments. Comparison of straightness measurements in 1990 and 2011 showed that crooks observed at the time of first thinning were not visible 21 years later (Figure 4).

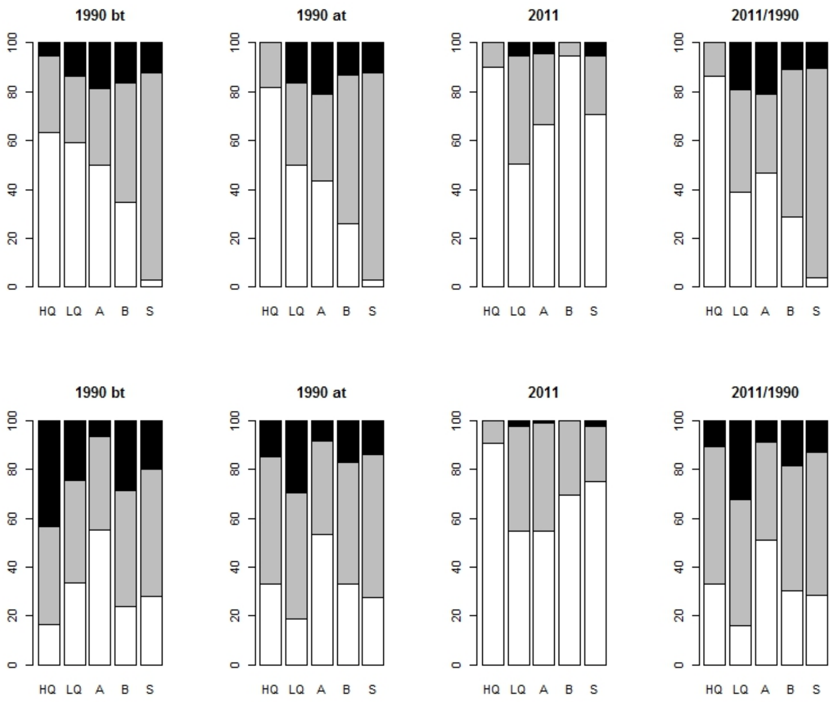

Figure 4. Frequencies of straight (white), crooked (grey) and severely crooked (black) trees at the time before first thinning (1990 bt), after the first thinning (1990 at) and after the second thinning (2011) at Taberg (upper row) and Sandhage (bottom row).

Before the first thinning on average 27% and 39% of trees had recorded defects at Taberg and Sandhage, respectively. After two thinnings, HQ plots had the highest proportions of trees with no quality defects (>90%) at both sites. The selection of low quality trees (LQ) resulted in the highest proportions of trees with quality defects in 2011 (Figure 5). Comparison of trees with defects in 2011 with the same trees in 1990 showed that after 21 years there was a higher frequency of trees with no quality defects than at the time of the first inventory (Figure 5).

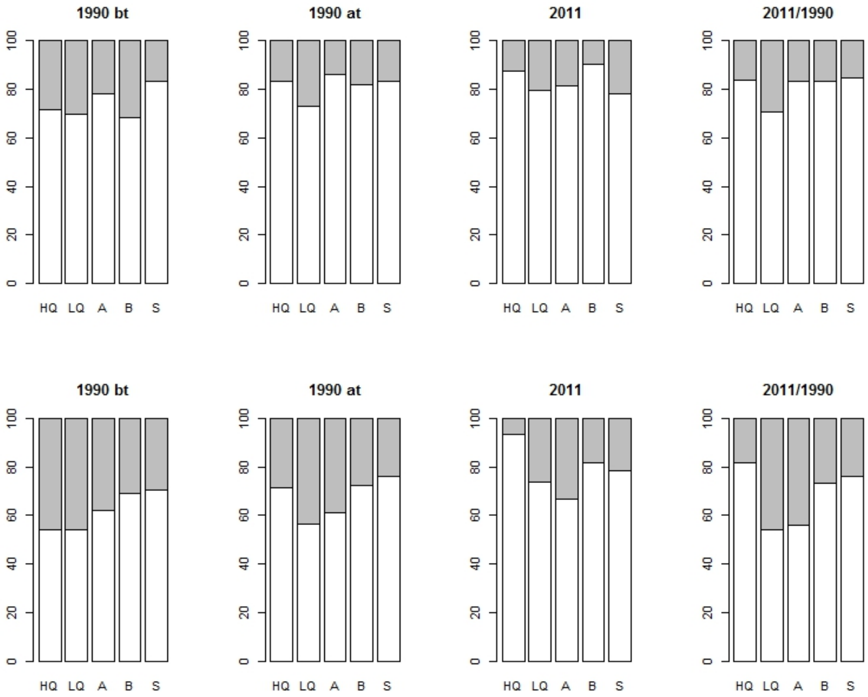

Figure 5. Frequencies of trees with no recorded quality defects except crooks (white) and with quality defects (grey) at the time before first thinning (1990 bt), after the first thinning (1990 at), and after the second thinning in 2011 at Taberg (upper row) and Sandhage (bottom row). The fourth column shows frequencies of these trees that had been left in the stand until 2011.

3.4 Paper IV

3.4.1 Materials and methods

The experimental stands analysed in this study are located in Vesslarp (Figure 1) close to the town Lönsboda and comprise parts of a long-term thinning-fertilization experiment established across Sweden in Norway spruce and Scots pine stands (Eriksson & Karlsson, 1997). Two plots thinned from below (T) and two unthinned plots (U) were chosen for analysis in this study. One thinned (T+F) and one unthinned (U+F) plot were subjected to nitrogen fertilisation at five-year intervals during the first 20 years after first thinning, and thereafter at seven-year intervals. Each plot covered 0.1 ha and was surrounded by a 10 m wide border zone that was subjected in each case to the same treatment. In the thinned plots, three thinnings were applied from below.

The basal area after thinning was reduced by 29-35% and 24-40% in the T and T+F plots, respectively.

Four high-quality, dominant trees that would be present in the final stand, according to visual assessments, were randomly selected from the border zone of each plot. Two logs were taken from each of these trees according to the pattern shown in Figure 6 and logs were sawn in a saw-mill according to the pattern shown in Figure 7. Half of each log was sawn into 22 mm planks (B) while the other half was sawn into 55, 50, 38 or 22 mm boards (A). In both patterns the aim was to maximise the production of sawn products. The boards were subsequently dried in the open air for about 2 months with a top cover.

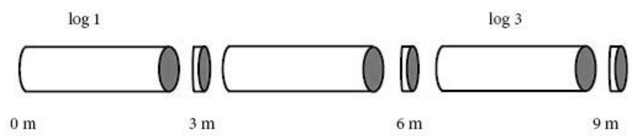

Figure 6. Sample material: two logs were taken from each sample tree according to the pattern shown.

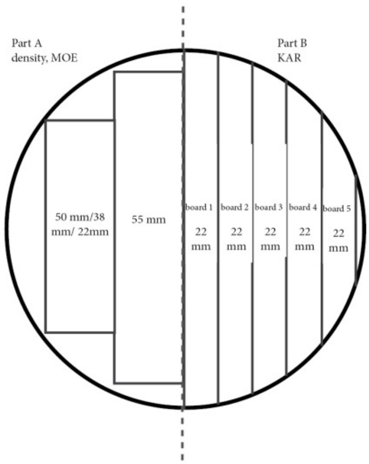

Figure 7. Sawing pattern and dimensions of produced boards. Vertical lines indicate saw kerfs and the numbers inside indicate the thickness of produced boards in mm.

The boards from the B part of the logs were scanned using a “WoodEye” sawn-products quality control scanner supplied by Innovativ Vision AB. The scanner uses black-white images and tracheid data to find knots and other visible defects on the surface of sawn material (Petersson, 2010; Anon, 2008a). In the study, black and sound knots were investigated as well as fibre distortions close to the knots. The KAR, the ratio of knot area to the cross-sectional area of the piece of wood was calculated, for each knot type and for all boards used in the study.

All boards were scanned and a data set of the observed defects was produced. A colour-picture of each side of each scanned board was taken to compare its visual appearance with results obtained by the scanner (Figure 8).

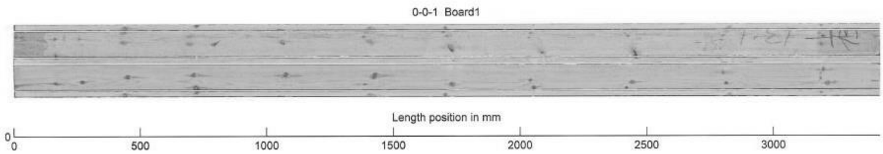

Figure 8. Example of a board image derived from the WoodEye scanner.

The dynamic MOE of boards from the A part of the logs was measured using the resonance frequency in the axial direction following Larsson (1997). At the same time the weight and dimensions were measured to calculate the boards’ density.

3.4.2 Results

The thinning treatments had no significant effects on the density, MOE or KAR of the boards ($p>0.05$, Figure 9). There were significant differences in all traits except KAR between logs 1 and 3. Both wood density and MOE were smaller in the third log.

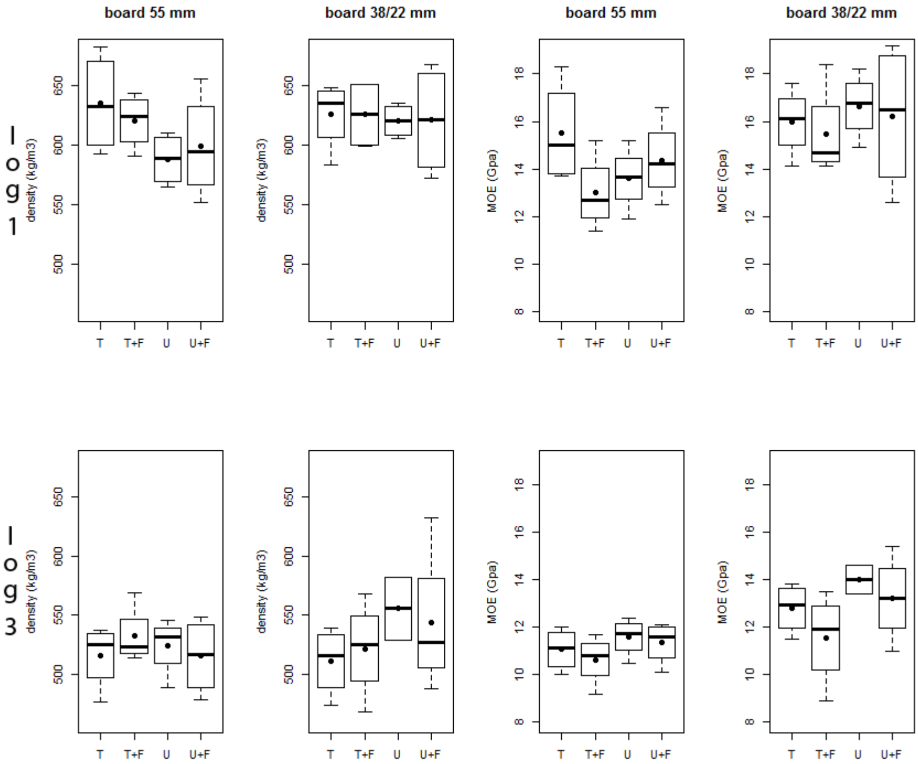

Figure 9. Wood density and MOE of the studied logs. Dots show the mean density. The first and second rows of figures show the wood density of log 1 and 3, respectively. Board 55 mm indicates boards from the logs' central part while board 38/22 mm indicates boards from outer parts.

The KAR of dead knots was higher, on average, in the first log while the KAR of live knots was higher, on average, in the third log (Figure 10). The KAR of dead knots in the first log generally increased up to the third board (except in logs from the U plots) while the KAR of live knots successively decreased from the first board outwards. In the third log, the KAR of both dead and live knots increased with increasing distance from the pith (Figure 10). However, there were no significant between-treatment differences in KAR values for either dead or live knots.

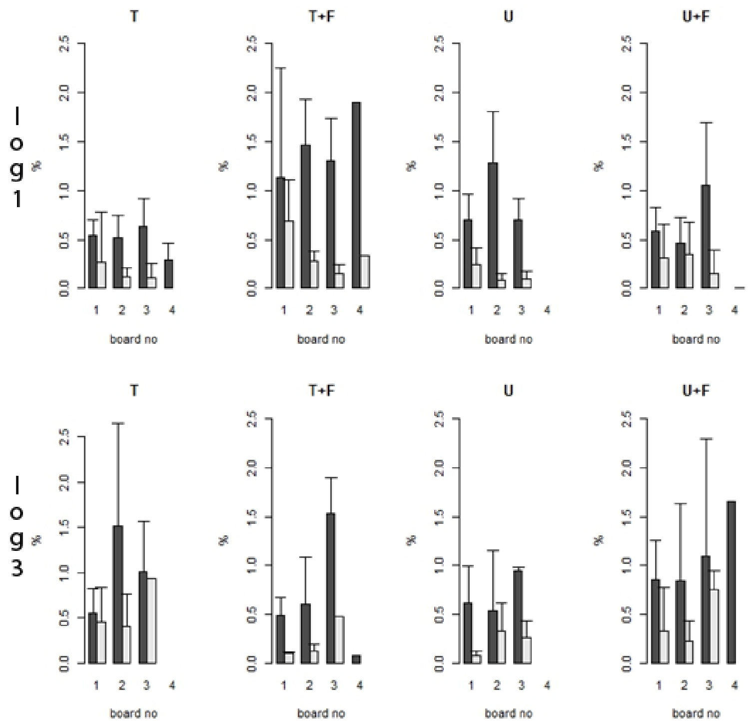

Figure 10. Knot area ratio (KAR) under all treatments. Bars show the mean value of KAR (black – black knots, grey – sound knots). The vertical line at the top of each bar shows the standard deviation of the mean value. The upper row of figures shows data for log 1 (0-3 m) while the lower row shows data for log 3 (6-9 m).

There were small between-treatment differences in the average dbh of the 260 thickest trees per ha (Figure 11). The trees were on average 1.7 cm thicker in the T than in U.

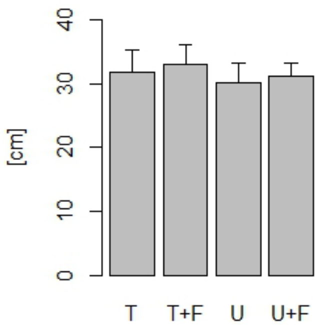

Figure 11. Mean diameter of the 260 thickest Scots pines per hectare under the thinning treatments applied in Study IV.

3.5 General comparison of experiments

The variation of quality traits observed at all four experimental sites is shown in Table 3. The differences between species planted at the same spacing were small. The diameter of the thickest branch increased with increases in spacing. Spacing had little effect on straightness, but frequencies of spike knots and double tops tended to increase with increasing spacing. The subjectively judged quality of the stems varied between the analysed experiments.

Table 3. Variations in quality traits with spacing observed in the studied stands.

Experiment	Species	Spacing	Thickest branch	Straightness class I	Quality class I	Spike knots	Double tops
		[m x m]	[mm]	[%]	[%]	[%]	[%]
Remningstorp (Paper I)	Scots pine	1 x 1	11	75	39	22	16
		2 x 2	20	65	46	40	19
		3 x 3	24	58	41	55	30
Hässelby (Paper II)	lodgepole pine	1.41 x 1.41	15	84	69	17	4
		2 x 2	20	76	39	27	9
		2.83 x 2.83	24	82	24	29	14
		4 x 4	34	71	3	28	21
Bockemålen (Paper II)	lodgepole pine	1.41 x 1.41	13	93	70	18	9
		2 x 2	16	88	47	29	24
		2.83 x 2.83	17	86	53	31	17
		4 x 4	22	92	52	36	10
Asa (Paper III)	Norway spruce	2 x 2	15	50	37	14	-
		2 x 2	15	33	22	28	-

There was a clear correlation between dbh and diameter of the thickest branch closest to breast height at all experimental sites (Figure 12). However, the correlations were lower in the Norway spruce stands, on average, than in the pine stands.

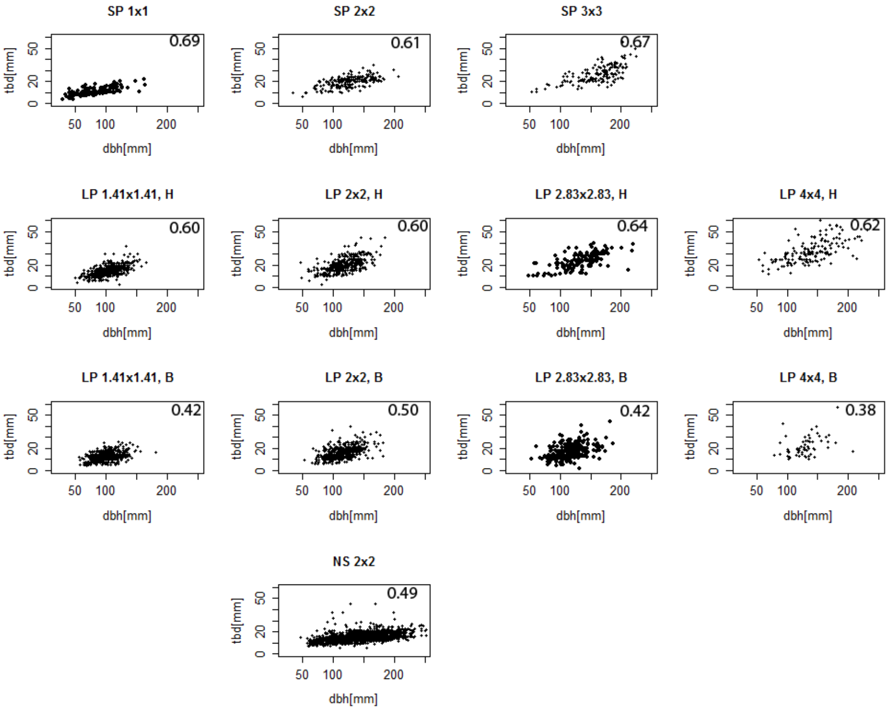

Figure 12. Relationship between dbh (x-axis) and diameter of the thickest branch (Norway spruce) or thickest branch in the three whorls closest to breast height (pines), in both cases designated tbd (y-axis). SP – Scots pine (Paper I), LP – lodgepole pine (Paper II, H - Hässleby and B - Bockemålen), NS – Norway spruce (Paper III). The numbers in the right-upper corner of each figure are correlation coefficients.

4 General discussion

The following discussion begins by describing the growth and quality variation of trees in planted Scots pine, lodgepole pine, and Norway spruce stands at the time of first thinning (section 4.1), focusing on the scope for selection possibilities and its dependence on initial spacing. The discussion continues with consideration of the potential value of improved planting material in Scots pine stands (section 4.2). Short- and long-term effects of different selection strategies applied at the time of first commercial thinning in Norway spruce stands are then discussed, focusing on their effects on quality traits (section 4.3). Finally, thinning effects on quality properties of Scots pine boards are addressed (section 4.4).

4.1 Effects of initial spacing on future timber quality and selection possibilities

The studies presented in Papers I-III provide information on both the structure and variations of growth and timber quality properties at the time of first thinning in monocultures of three coniferous species growing in southern Sweden. The initial variation of quality traits sets scope to influence stand quality by selecting trees in further thinnings (Klang, 1999). The acquired data show the possibilities to select high quality trees at the time of first thinning in Scots pine and lodgepole pine stands at several spacings, and Norway spruce stands at 2 x 2 m spacing.

In Studies I and II reductions in frequencies of high quality trees with increases in spacing were found. For lodgepole pine (Paper II) there were significant differences in this respect between the 1.41 x 1.41 m and 4 x 4 m spacings. In contrast, no significant differences were found between the three analysed spacings (all except 4 x 4 m) in Scots pine stands (Paper I), although quality tended to decline with increases in spacing (Table 3). At the 2 x 2 meter spacing, 65% of the Scots pine trees were straight. This is substantially higher than the percentage (25%) Agestam *et al.* (1998) found in a 35-year-old Scots pine stand planted at this spacing. Huuskonen *et al.* (2008) found that on average 54% of Scot pines in young stands in Finland had no quality defects. The most frequent of the analysed defects were crooks (23%), followed by high branchiness (9%), and they were more frequent in planted than in naturally regenerated stands. The lack of straightness in planted Scots pine stands is a known phenomenon (Agestam *et al.*, 1998; Ekö & Agestam, 1994). As yet there is no scientific explanation for the differences between planted and naturally regenerated trees, although several hypotheses have been postulated based on ratios between roots and shoots in planted stands, and/or root architecture after replanting. In the study by Agestam *et al.* (1998) the same provenances were used in both naturally regenerated and planted plots, and significant differences between them were found.

The mean diameter of the thickest branch increased with increasing distance between trees (Table 3), in accordance with numerous findings for various species (e.g. Pfister et al., 2007; Agestam et al., 1998; Johansson, 1993). In the analysed stands there was great variation in the thickest branch diameter among trees with a given dbh (Figure 12). The thickest branch distributions of Scots pine and lodgepole pine indicate that there is some potential for selecting thick trees with relatively thin branches growing in spacings up to 3 x 3 m. This conflicts with previous findings of only poor quality trees at 2.5 x 2.5 m spacings (Agestam *et al.*, 1998). The differences in results may be at least partly due to differences in site index between the experiments. Site indices were not evaluated in Study I, but site indices for the planted stands examined by Agestam *et al.* (1998) ranged from 25.8 to 29.6 m. It can be assumed that conditions vary among sites due to variations in soil, climatic and other environmental factors. Persson (1977) found that the importance of initial density decreases with reductions in site index. In Norway spruce plantations with 2x2 m spacing the possibility to select thick trees with relatively thin branches is even higher as the branch distribution curve is flatter. In Study III, relatively big trees were found to produce wider annual rings on average than smaller trees. Thus, thick trees with small branches could potentially be targeted for retention during thinnings. Moberg (1999) found that application of the same thinning program in Scots pine stands established at spacings ranging from 1.5 to 2.5 m caused the equalisation of branch diameter, especially in the upper part of the stem.

The reductions in frequencies of high quality trees with increasing spacing have to be considered in connection with reductions in numbers of seedlings, as both will clearly result in lower numbers of high quality trees that are likely to be selected as future crop-trees. The frequency of such trees will be further limited by unselective removal on strip roads (Klang, 1999) and the necessity to maintain regular spatial distribution in the remaining stand for high volume production (Pretzsch, 2009; Fahlvik, 2005). However, corridor PCTs and thinnings, which have been recently found to have no significant effects on volume production in comparison to selective thinnings in Scots pine stands (Karlsson *et al.*, 2013) might change this approach. It was shown in Study III that the highest quality trees are not always evenly located in a stand. Clustering of high quality trees might reduce wood quality in such stands since selection of trees is restricted by the aim to achieve regular distribution in order to promote volume growth (Pretzsch, 1995).

Coniferous stands, which dominate in forests of southern Sweden, are highly exposed to several risk factors. Root rot and wind damage currently cause the most substantial economic losses (Bengtsson & Nilsson, 2007; Bendz-Hellgren *et al.*, 1998; Valinger & Pettersson, 1996). Stands examined a few years after thinning have been found to be highly damaged by wind (Valinger & Pettersson, 1996; Quine *et al.*, 1995). Plantations with wider spacing have been suggested as options to reduce the risk of such damage (Barry *et al.*, 1998). Trees in wide initial spacing should have higher wind stability than trees at similar sites in narrower spacings due to a higher stem taper (Sjolte-Jorgensen, 1967). Avoiding thinnings during rotation might be an option to reduce the risk of root rot spreading, since stumps of thinned trees will not be exposed to spores of the fungi. Vollbrecht (1994) found that the number of thinnings and thinning intensity are related to the spread of butt rot. However, spacings and numbers of thinnings have conflicting effects on volume, quality and risks (Pfister, 2007).

There were about 2000 trees/ha^{-1} at the time of first thinning in the Norway spruce stands (Paper III). The analysis showed that high quality trees can be selected on the basis of straightness and stem defects. The main advantages of these traits are that they are easy to observe during selection and they are strongly related to wood quality (Klang, 1999).

There were no obvious differences between the examined pine species with respect to external quality properties (Table 4). The differences between the pines and Norway spruce at 2 x 2 m spacing were also small, and frequencies of quality defects were similar for all species at the same spacing (Table 4). However, industrial requirements regarding quality of these species differ, being much higher for Scots pine than for Norway spruce timber (Anon, 2008b), thus thinning regimes must be much more carefully considered for Scots pine stands.

Practical implications

The spacing currently used in practical silviculture of coniferous species in Sweden is 2 x 2 m. The negligible differences in values of quality traits between 2 x 2 and 3 x 3 m spacing suggest that further reductions in initial densities could be considered, as discussed for Norway spruce stands by Pfister (2007). Trees growing at wider initial spacings are often influenced by natural regeneration of Scots pine and birch, which reduces initial distances between seedlings and might enhance future timber quality. Thus, the optimal density for specific sites is dependent on local conditions, and when considering the scope for reducing seedling densities particular attention should be paid to the selection regime as frequencies of high quality trees will also decrease. Poor selection in thinning might result in poor quality logs that will not be industrially acceptable, even with current rather liberal requirements.

4.2 Interactive effects of family and spacing on the quality of timber in planted Scots pine stands

The detected significance of spacing x family interaction indicates that families' performance is influenced by spacing. Significant interactions presented in Paper I were restricted almost exclusively to the growth traits, except for occurrence of spike knots. The strongest interactions were found in early measurements, when the spacings provided different competitive environments. There have been few studies on the effects of environment-genotype interactions in Scots pine stands, making it difficult to compare the findings to previous observations. However, Persson (1995) found significant family x spacing interaction effects on the total yield, but not the volume of individual trees or basic density of Scots pine. The material in the cited study was limited to five local provenances. Investigations of other species have provided conflicting indications of spacing x family interactions, but most have detected significant effects on quantitative traits up to 20 years after planting. Ye *et al.* (2010) and Aspinwall *et al.* (2011) found several significant interactions for quantitative traits in the early development of Douglas fir stands, but not Stoehr *et al.* (2010). In 17-year-old Radiata pine (*Pinus radiata*) stands in New Zealand significant interactions between genotype and initial spacing have been found for most growth traits, including height, dbh, and both crown base height and diameter (Beets & Kimberley, 1993).

Practical implications

The findings might have major implications for the management of stands established from genetically improved material, which is often used in practical forestry in Sweden (Skogsstyrelsen, 2013b). The results indicate that new testing experiments are needed if either increases or decreases in planting densities are planned, because recent recommendations for planting improved material are derived from study plots established with other spacings. In fact, neither 1 x 1 m nor 3 x 3 m spacing is currently commercially used in the Swedish forestry sector. As stated in section 4.1, planting densities may be gradually reduced to avoid thinnings and thus maintain profitability and/or reduce risks of root rot and wind damage. The results acquired in the presented studies suggest that it could be relevant to test currently recommended planting material at other spacings to confirm its usefulness in changing silvicultural practices.

4.3 Effects of selection method on external quality traits in Norway spruce

Removing trees is one of the most important measures to steer stand development in terms of quality and individual tree growth (Pretzsch, 2009; Macdonald & Hubert, 2002). From an economic perspective this will lead to increases in the value of residual trees. Study III showed that it is possible to obtain high quality Norway spruce stands by selecting trees with high quality properties in the first thinning.

Straightness and severe quality impairments (spike knots and double tops) are the most important traits when assessing the quality of spruce logs (Anon, 2008b). The careful selection of high quality trees (HQ treatment) resulted in the highest proportions of straight trees (Figure 4). At the time of first thinning all quality traits are visible on the lower part of the stems and can be used as selection criteria. At the time of the last inventory, when the stand was about 50 years old, some of the quality traits (e.g. branches, crooks and spike knots) were no longer visible. However, such defects will be present in future sawn-wood, especially crookedness. Under the S treatment in the Taberg experiment only 1% of trees were straight at the time of the first inventory, while at the time of the last inventory the proportion was close to 70%, possibly due to overgrowth of existing crooks (Figure 4) (Szeligowski *et al.*, 2010). However, even if crooks are overgrown their presence will affect the quality of sawn-goods from trees harvested at rotation age during final felling, as trees with overgrown crooks or bends will contain higher than usual percentages of compression wood (Green *et al.*, 1999). Overgrowth might also explain the changes in frequencies of trees with no quality defects as occlusion of spike knots may have made it impossible to observe them (Figure 5).

There were small absolute between-treatment differences in branch diameter after two thinnings. This is not surprising as other traits had higher selection priority. However, comparisons of thinned and unthinned stands showed that thinning positively affected the natural pruning rate. Mäkinen (1999a) found that it was possible to improve the quality of first logs in Scots pine stands by delaying thinning and thus reducing branch growth, however this provided little opportunity to reduce timber knottiness. The impact of branch traits on the logs could be improved only at the expense of growth, which would prolong the rotation (Mäkinen, 1999b). The distribution of the thickest branches in relation to dbh showed that there is potential to select thick trees with relatively thin branches even among dominant and co-dominant trees (Figure 12). However, a reduction in average diameter of the thickest branch will not necessarily decrease the KAR of products as even dead branches might remain on a stem for a long time.

Branches remained for a longer time on stems in unthinned stands than in thinned stands, which leads to production of wood with higher knot contents and KAR. Simulations by Ikonen *et al.* (2009) suggest that the rate of natural pruning is high in relatively sparse stands of Scots pine, and Heikinheimo (1953) found that thinning promoted self-pruning. The biological processes involved were not elucidated in the cited studies, but thinnings increase wind speeds, precipitation and solar radiation in stands, which might hypothetically accelerate natural pruning rates (Heikinheimo, 1953). Mäkinen & Colin (1999) found that natural pruning was faster on large trees with long crowns than on thin trees with short crowns. In addition, branches in stands might fall during thinning operations when trees are felled. Mäkinen (1999) found that dead branches might stay on Scots pine stems for 40 years, and findings presented in Paper III indicate that self-pruning may take as long in Norway spruce as in Scots pine. Thus, there may be too little time for overgrowth of branches during the rotation and (hence) production of knot-free timber.

In Norway spruce stands Braastad and Tveite (2000) found only 1.9 cm differences in the mean dbh of the 600 thickest trees between stands heavily thinned from below and unthinned stands 40 years after last thinning. Similar results have been found for both Scots pine and Norway spruce stands in the large-scale thinning-fertilisation experiment in Sweden (Paper IV; Nilsson, 2013, pers. comm.; Figure 11). These results indicate that there are no justifications for thinning merely to enhance dbh development of the thickest trees. Timber volume from the thickest, and thus probably most valuable, trees will be similar as there are also strong indications that height is not influenced by thinning programs. Thus, the aim of thinnings should be to produce timber of the highest possible quality. There should be clear differences in wood quality of the thickest trees in thinned and unthinned stands as selection allocates growth to chosen trees. Self-thinning is heavily dependent on numerous variables, including micro-site conditions and genotype. Hence, it is considered a stochastic process, and growth of even poor quality trees might be promoted in unthinned stands.

Practical implications

It is possible to observe traits related to timber quality in the first thinning, and thus enhance the future quality of the stand by selection. Thinning early and quite heavily will also reduce the risk of wind damage (Sehlberg-Samuelsson *et al.*, 2009). This study indicates that the thinning strategy will not significantly decrease volume production, even if poor quality or small trees will be retained in the stand. This finding is also supported by other studies (*cf.* Nilsson *et al*, 2010). In mechanised thinning systems there is limited possibility for selecting individual trees, focusing on specific quality traits, partly because there are high demands on machine operators for efficiency and only one side of each tree can be inspected from the cabin. Furthermore, light conditions are often poor, especially during night shifts. The schematic cuttings when making strip roads further decrease selection possibilities. Manually marking trees to harvest could not currently be financially justified, since market prices do not favour production of high quality Norway spruce timber. However, this situation might change in the future.

4.4 Thinning effects on Scots pine sawn timber quality

The observed frequencies of quality defects and high quality trees in planted Scots pine stands (Study I) highlight the importance of selection in thinning as a tool to produce high quality timber. Careful selection of trees in thinnings concentrates further timber production in trees with desired quality parameters.

However, Study IV did not confirm the hypothesis that quality could be improved by thinnings, at least in terms of wood density, MOE and KAR. There were no significant differences in the studied traits between thinned and unthinned stands. Unfortunately, a lack of similar studies makes it difficult to compare these results with previous findings. Ulvcrona and Ulvcrona (2011) found no significant differences in MOE and late wood density between young, pre-commercially thinned Scots pine stands and others that had been pre-commercially thinned and fertilized. However, early wood density was significantly influenced by the studied treatments. Jaakkola *et al.* (2006) found no thinning effect on Norway spruce density, although it positively affected radial growth rates. For Norway spruce Pfister (2007) compared five thinning programs and found no significant differences in quality parameters except KAR in the central board from the first log. Furthermore, differences were significant only between unthinned stands and stands subjected to a single heavy thinning with reduction of basal area to 11 m^2/ha^{-1}.

Heikinheimo (1953) found that thinning promoted the self-pruning of dead branches and this was corroborated by simulations presented by Mäkinen and Colin (1999). However, the factors that might cause faster self-pruning in thinned stands were not identified. In Study III it was found that trees retained branches longer in unthinned stand than in thinned stands. This, together with wider annual rings, indicates that the amount of knot-free timber should be higher in thinned stands. However, the hypothesis that thinnings may promote increases in amounts of knot free wood with increasing distance from the pith was not confirmed in this study. Only MOE in outer board were significantly higher than MOE in boards from the pith. The boards from outer parts of the stems did not exhibit significantly different values of wood density and KAR. However, there were small absolute differences between the mean values for boards from different locations in the logs, which could be regarded as indications of a positive effect of thinning. However, few outer boards (more than third from the pith) were examined and there were only two fifth boards from the pith.

Scots pine trees are known to retain branches for a long time even after thinning (Ikonen *et al.*, 2009; Mäkinen, 1999a; Valinger, 1993). Mäkinen (1999b) found that complete occlusion of a branch only occurs about 40 years after its death. The first commercial thinning in the studied stands was done at the age of 47 years, when (presumably) most of the branches on the lowest part of the stem were already dead, since the stand was naturally regenerated. Although no information about the regeneration is available, it was probably successful as well-developed, homogenous stands were chosen for the thinning and fertilization experiments. It is well known that stand density strongly influences branch diameters and branch mortality in Scots pine stands (Agestam *et al.*, 1998; Mäkinen, 1996). Trees in naturally regenerated stands have significantly thinner branches than trees planted at 2 x 2 m spacing (Agestam *et al.*, 1998), and branch death starts earlier due to faster canopy closure. In the studied plots the process of branch occlusion had already started at the time of first thinning. Hypothetically, thinnings should have accelerated this process as some branches might have been accidentally pruned during harvesting. The sparser distribution of trees after thinning should also accelerate the shedding of dead branches by increasing wind speeds, precipitation and solar radiation in the stand (Ikonen *et al.*, 2009; Heikinheimo, 1953). Although the hypothesis that thinning has positive effects with respect to branches was also not confirmed, it should be noted that the dbh distribution differed between treatments and that the trees were thicker in thinned plots than in unthinned plots. Thick trees in this study produced more boards than thin trees and the additional boards were almost entirely free of quality defects. Thus, the positive effect of thinning might be attributed to the acceleration of dbh growth and, thus, higher numbers of sawn-products. However, there were only two 5th boards from the pith so this conclusion must be treated cautiously.

The lack of significant between-treatment differences in most analysed traits might also have been partly due to the rather limited empirical material used in the study. Sample sizes were probably too small to detect some treatment-effects in the noise generated by within-stand variation. In support of this hypothesis, Moore *et al.* (2013) attributed 75% of variation in selected traits of Sitka spruce to within-stand differences.

Important internal quality traits, such as warps, twists and springs were not investigated in the presented study. However, all plots in the study were homogenous at establishment time. Thus, differences in these traits were unlikely to be present as boards sawn close to the pith are more likely to have twists and springs than boards from the outer parts of the stem, mainly because boards from the central part have higher juvenile wood contents (Johansson *et al.*, 2001). In addition, the first thinning was done when the plots were 47 years old and presumably all trees had similar proportions of juvenile wood as the whole stand was managed consistently until that time.

4.5 Management implications

- ✓ Timber quality in Norway spruce stands might be improved by careful selection. However, the opportunities for this are highest in the first thinning when traits are easily observed.
- ✓ At the conventional spacing of 2 x 2 m there is high between-tree variation in quality traits, indicating that that there is scope for selecting high quality trees. Since there are rather weak correlations between tree size and quality parameters, the selection should focus on specific properties, e.g. straightness, visible defects and branches.
- ✓ Straightness and the presence of severe quality defects could be used as selection criteria.
- ✓ The negligible differences in relative values of quality traits in Scots pine and lodgepole pine stands planted at 2 x 2 and 3 x 3 m spacings indicate that planting densities could be further reduced without substantially impairing selection possibilities.
- ✓ There were no indications that the quality of lodgepole pine will be inferior to Scots pine when planted at the same density. Thus, lodgepole pine might be an attractive alternative species as it is less browsed than Scots pine.
- ✓ There were also indications in Study II that natural regeneration of other species might provide a way to improve stem quality. Thus, the optimal planting density for specific stands is dependent on local conditions.
- ✓ The lodgepole pine study showed the potential to produce timber of suitable quality in stands of the species with the conventional spacing of 2 x 2 m. It did not support previous findings from northern Sweden that lodgepole pine is more productive than Scots pine. However, more studies are needed to draw robust conclusions in this respect.

4.6 Limitations and future research

- ✓ The presented results are difficult to generalise as they were obtained from rather small-scale experiments that do not cover the whole range of potentially important factors, e.g. site indexes. In addition, their design precludes rigorous statistical tests to detect differences between treatments. Furthermore, the selection of trees for sawing in Study IV was not entirely appropriate (as discovered during the data analysis). The thickest trees should have been chosen for sawing to compare the quality of outer boards between thinned and unthinned stands. Nevertheless, the results provide potentially important contributions as there are few such analyses of forest production due to funding constraints.

- ✓ Scots pine stands corresponding to those used for analysing effects of different thinning strategies on Norway spruce stands are available and could be used to address the same questions. Furthermore, such analysis might be even more relevant as high quality Scots pine is more valuable than high quality Norway spruce wood.

- ✓ The potential advantages of allowing the establishment of lodgepole pine plantations in southern Sweden (where coverage of Scots pine is dramatically declining) have been discussed. Study II did not confirm that it offers superior production to domestic pine, but it may still be an attractive alternative. Thus, it will be interesting to test lodgepole pine growth, especially on poor sites in southern Sweden.

- ✓ Effects of thinning regimes on the natural pruning of branches have not been studied. Thus, if any new planting experiments are established to study long-term thinning effects it would be relevant to include treatments designed to assess effects on natural pruning rates.

- ✓ There is also a need for more studies to determine effects of whole chains of silvicultural interventions on the quality of sawn products. Such studies are expensive but valuable, and Study IV demonstrated a possible approach.

- ✓ Interest in cultivation of mixed stands and continuous-cover-forest stands (CCF) is gradually increasing in Sweden. These new silvicultural methods have been found to deliver wider ranges of ecosystem services than traditional monocultures, especially in terms of biodiversity and water quality (Gamfeldt *et al.*, 2013). However, many Swedish forest owners require more information about the effects of shifts towards mixed and CCF forest on timber quality. A few experiments have been established in Sweden recently to study these effects, and will eventually provide suitable material for addressing timber quality issues.

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