

Chapter 9

Wood Properties and Quality



Riikka Piispanen, Jiri Pyörälä, and Sauli Valkonen

Abstract

- Trees in continuous cover forestry (CCF) typically form very narrow rings at young ages in suppressed positions but can grow very quickly at older ages in dominant positions, maintaining long-lived crowns.
- CCF trees have slightly higher mean wood density in stems than rotation forestry (RF) trees.
- CCF trees have better fiber properties for pulp than RF trees.
- CCF trees have a relatively short stem section of small dead knots in sawn timber.
- CCF trees have a relatively long section of large green knots in sawn timber.
- Sawn goods produced from spruce logs yielded with the selection system do not differ markedly from those from RF.
- The application of a shelterwood system with overstorey retention for Scots pine facilitates the production of very high-grade timber.

Keywords Wood quality · Wood density · Fiber dimensions · Timber quality · Juvenile wood

9.1 Introduction

Wood properties and quality in uneven-aged stands are key focus areas in the debate that has taken place in the Nordic region since the 1980s about the pros and cons of continuous cover forestry (CCF). Expectations regarding the production of potentially high-quality sawn timber have been one of the arguments in favour of

R. Piispanen · S. Valkonen (✉)
Natural Resources Institute Finland (Luke), Helsinki, Finland
e-mail: sauli.valkonen@luke.fi

J. Pyörälä
Department of Forest Sciences, University of Helsinki, Helsinki, Finland
e-mail: jiri.pyorala@helsinki.fi

CCF, as most of the wood harvested from CCF stands is sawlogs. However, in addition to sawlogs and sawn goods, attention should be paid to properties that impact pulp making. A large portion of the harvested volume is used for making pulp from culled logs that are unsuitable for producing lumber, and from chips produced from the outside of the logs during lumber manufacturing (slabs, chips, and sawdust).

Scientific knowledge about the effects of CCF on wood properties and quality in both sawn timber and pulp is limited, and arguments have been based on general knowledge regarding wood quality in even-aged forests. Very few studies have directly focused on wood properties in trees grown under any of the CCF regimes in the Nordic countries. The global situation is not much better. However, studies conducted in stands at various stages of transformation from rotation forestry (RF) to CCF are more common and very relevant (e.g., Pape 1999; Seeling 2001; Macdonald et al. 2010, see review by Pretzsch and Rais 2016).

There is one rather unique Norwegian study on wood quality in Norway spruce, based on 35 mature ($d > 28$ cm) sample trees in seven experimental selection stands. The study focused on the ring profile and density at different heights along the stems, mechanical, technical, and physical wood properties measured on small immaculate samples, and timber strength of standard structural sizes (Eikenes et al. 1995). An earlier Norwegian review focused on the basic quality traits, and factors influencing them, of wood from the selection and shelterwood methods (Vadla 1992).

Fagerberg et al. (2023) produced a simulation framework for modeling knot size for uneven-sized Norway spruce stands with the competition-dependent approach in Sweden. At this stage, the data has only originated from one stand, but provides some important perspective to the topic.

Most comprehensive information on wood properties and quality in CCF trees comes from a series of intensive studies conducted in Finland in stands that are part of the ERIKA experimental set on single-tree selection in Norway spruce stands in southern Finland (Pyörälä 2013; Piispanen et al. 2014; Kumpu et al. 2020; Piispanen et al. 2020; Pyörälä et al. 2022). In these experimental stands, a single-tree selection system was adopted in the 1980s for the maintenance or establishment of typical complex stand structures to resemble the classic “Plenterwald” system. Selection harvests were carried out 3–4 times before the data was collected in 2007–2011 from nine stands at three sites (Lapinjärvi, Vesijako, Suonenjoki). All stands at that time could be characterized as truly multi-aged (with tree ages up to 170 years) and most were also full-storied (in the sense of Ahlström and Lundqvist 2015). In connection with a single-tree selection harvest, a total of 156 sample trees were acquired on the plots. The trees were felled and measured on site and in the lab for a number of wood quality variables at fiber, annual ring, stem disc, log, stem, and branch levels.

Based on these studies, this chapter largely concentrates on the following wood properties and quality traits in Norway spruce grown under the selection system, with reference to the influences of stand structure and tree dominance:

- Growth rates and patterns (ring profiles and branching patterns)
- Wood density
- Fiber dimensions

- Quality of sawn timber (twist and other distortions, knottiness, other quality traits, and strength and quality grading results)

At the end of the chapter, we briefly consider timber quality in two-storied Scots pine stands originating from shelterwood cuttings with subsequent partial overstorey retention. Some basic considerations but few research results are available in the Nordic area for Scots pine (review by Vadla 1992), while much more work has been done in Germany on scientific and practical aspects. These are briefly reviewed.

9.2 Selection Silviculture with Norway Spruce

9.2.1 *Tree Growth Patterns*

Silvicultural practices are used to control the environmental factors that influence tree growth and wood formation and properties (Wimmer and Downes 2003). Based on this general knowledge, wood properties can be expected to differ between CCF and RF, as the typical growth rhythms of individual trees are distinctively different.

RF is characterized by uniform stands with a single dominant species, and with homogeneous spacing, stem diameter, height, and canopy structure. After clearcutting and reforestation, the emerging seedlings and young trees have ample resources and growing space at their disposal and, for a long period, they grow virtually free of competition from their neighboring trees. Consequently, their initial growth is very rapid. Later, the canopy closes, and competition gradually intensifies, suppressing tree diameter growth. Thinning will temporarily boost the diameter growth of the remaining trees. Growth is consistently relatively rapid, but with a slow decline from the initial maximum.

In contrast, the single-tree selection system in CCF is associated with a great degree of structural heterogeneity within and between stands. Stands are made up of trees of multiple ages and sizes, mixed at small spatial scales, resulting in complex competitive interactions between the trees. Trees typically experience consecutive suppression and release phases, especially at early ages (Schütz 2001; Erikäinen et al. 2014). Seedlings emerge from natural regeneration among the matrix of trees of all sizes. They are subjected to intensive competition, and their height and diameter growth is slow. The duration of this undergrowth stage varies considerably within and between stands. Many undergrowth trees must endure such unfavorable conditions for several decades. Others develop more rapidly while occupying growing spaces with lower stand density or in the presence of shade-intolerant tree species with a lower shading intensity. Seedlings and saplings that survive this stage will gradually be able to accelerate their growth as larger trees around them are gradually removed in repeated harvesting (Fig. 9.1). Growth will further accelerate when the tree has finally achieved a better competitive position in the intermediate and, especially, in the codominant and dominant layers. Diameter growth of the



Fig. 9.1 Slow growth at the undergrowth stage is shown as very thin annual rings near the pith at the tree base. Photo from the ERIKA experiment. Photo: Riikka Piispanen

large trees in a selection stand can be faster than that of their counterparts in an even-aged stand.

These differences have been documented in literature, for example based on the ring samples collected from the 96 Norway spruces in the ERIKA experiment (Pyörälä 2013; Piispanen et al. 2014, 2020) and 35 Norway spruces in the Norwegian study (Eikenes et al. 1995). These materials often contained very narrow rings near the pith covering a variable number of years up to several decades, depending on the length of the suppression period (Fig. 9.2). Trees that had obtained dominant canopy position by the time of sampling showed a rather stable ring width, with a modest initial increase and a gentle decrease in the later stages (Fig. 9.2). For the intermediate trees, ring width was smaller but increased throughout, while the suppressed trees displayed an increasing ring width at the later stages only. It should be noted that, with constant radial growth, tree basal area growth is amplified by default, as the annual growth ring (of equal width) becomes longer as it is added to a greater girth.

The typical growth pattern is most pronounced at the base of the tree where the rings have been formed during the lowest canopy position of the tree, i.e., in suppressed position. Further up the stems of large trees, the zone of narrow rings fades away as the canopy position improves, and the growth ring pattern becomes increasingly like that in trees from RF, where ring width is greatest near the pith and decreases steadily towards the bark (Eikenes et al. 1995; Pyörälä 2013; Piispanen et al. 2020). The results confirm that the characteristic slow initial growth and higher age in selection stands will not impede tree growth when the tree has risen into a

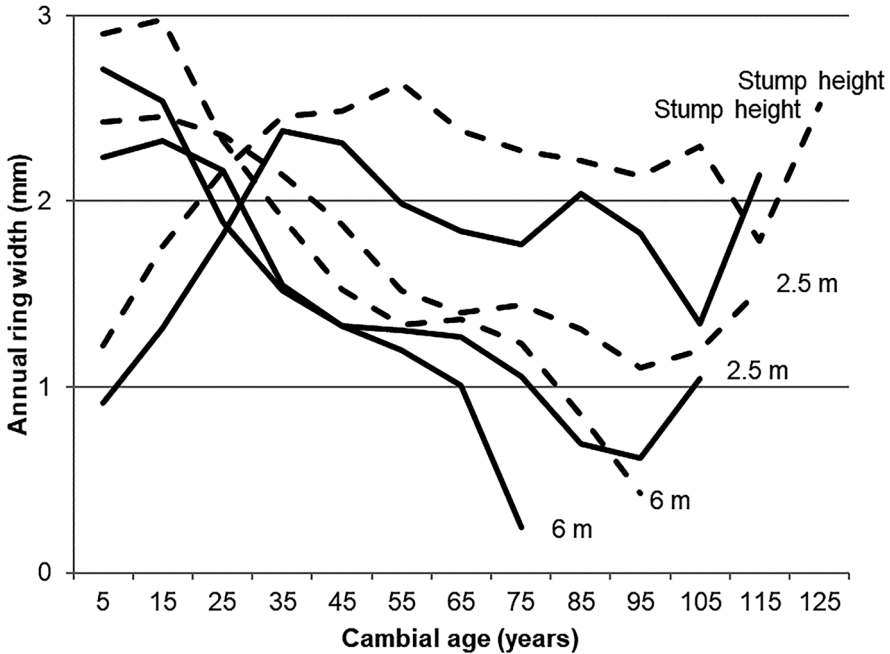


Fig. 9.2 Average annual ring width in Norway-spruce stands managed with single-tree selection by cambial age and by two tree size classes (solid line = 20–29.9 cm, dashed line = equal to or greater than 30 cm) at different heights along the stem (stump height, 2.5 m, and 6 m). Values are averages for the diameter classes of 10 rings, shown at class midpoints. Data from Piispanen et al. (2020)

dominant canopy position. The oldest trees in the ERIKA data were 170 years old, with about half of the period representing slow growth. However, they had grown quite normally during their last decades and had eventually become large ($d = 40\text{--}65$ cm).

An important consequence of the tree growth pattern in selection stands is that the trees tend to have many branches in their base section, but these remain thin and are shed rapidly (Fig. 9.3), appearing as small knots in the wood near the pith (Piispanen et al. 2020). Another feature arising from the differences in growth patterns and inter-tree competition is that large trees in selection stands have longer crowns (of living branches) than those in even-aged stands (Kumpu et al. 2020; Hasenauer and Monserud 1996). They have consistently more growing space and fewer strong competitors in their vicinity than in RF, where stands tend to become much denser towards the end of the rotation. Under intense competition pressure and mutual shading, branches in the lower canopy die off, and length of the live crown contracts. The branches remain attached even when dead, and are visible as loose knots in the wood. Consequently, the zone of live knots is longer in selection stands, but the zone of dead knots is shorter, and the wood has smaller knots than in RF. However, the inner sections near the pith at the tree base tend to have more small dead knots. In contrast, Fagerberg et al. (2023) concluded from simulations



Fig. 9.3 Trees in selection stands tend to have many thin branches at the undergrowth stage, which will remain as small knots in the wood near the pith in the base section of the tree. Photo Luke/Erkki Oksanen

with a novel competition-dependent model that the impact from local competition on knot size in Norway spruce trees was rather limited. The study was conducted in one uneven-aged stand treated with selective cuttings in Sweden, and this conclusion must be considered rather tentative.

In addition to the obvious differences in the ring profiles and branching patterns, many differences in wood properties and quality between CCF and RF regimes arise from the respective stand dynamics. Shifting canopy positions can be reflected in the wood properties of trees grown in selection stands. One of the most fundamental factors that contributes to these differences is the smaller share of juvenile wood in the mature selection trees (Eikenes et al. 1995; Piispanen et al. 2014). Juvenile wood (or corewood) is associated with poor quality traits like lower density, thinner cell walls, lower length and width, greater variation in fiber dimensions, greater fiber angle in the S2 layer of the secondary cell wall, lower latewood proportion, and lower strength (Vadla 1992). Juvenile wood generally encompasses the first 5–20 annual rings in Norway spruce, as defined by the degree of microfibril angle (Vadla 1992). In the ERIKA experiment, the juvenile wood region at the base of the stem extended 20 rings in the uneven-aged stands, and 10 rings in the even-aged comparison stands (Piispanen et al. 2014). These juvenile rings, very narrow in selection stands, extended 2–3 cm from the pith and constituted a minuscule proportion of the stem volume in the mature trees, when compared to planted trees in even-aged stands (e.g., Downes et al. 2002; Pyörälä et al. 2022), where initial growth is intentionally maximized. Greater ring width can also amplify the poor properties of the juvenile wood (Piispanen et al. 2014; Pyörälä et al. 2022).

9.2.2 Wood Density

Wood density is one of the most important and most frequently studied wood properties due to its effect on timber strength, pulp yield, and the biomass accumulation and carbon storage of the wood. Wood density is closely related to growth rates, and in selection stands, the tree growth patterns significantly affect wood density ring by ring. During the initial period of suppressed growth at the stem base, the first, very narrow annual rings tend to have very high wood density, with a subsequent decrease towards the bark beyond around 20 rings (Piispanen et al. 2020; Piispanen et al. 2014; see Fig. 9.4). Density then increases and finally levels off in the outermost part. A large earlywood content in the mature outerwood of the CCF spruces was also observed, but this was not significantly associated with low overall wood density, due to the relatively high latewood density in the old rings (Piispanen et al. 2014).

In RF, wood density is lowest close to the pith, reflecting rapid juvenile growth, and increases evenly towards the bark. Density profiles in the upper parts of the stems from selection stands resemble those from RF (Eikenes et al. 1995; Kumpu et al. 2020). Consequently, at the whole-tree level, wood density in selection stands is slightly higher than in RF stands (Kumpu et al. 2020).

In the ERIKA studies, the highest wood densities in the narrowest rings near the pith were over 600 kg/m³, and around 450 kg/m³ in the mature wood near the bark (Piispanen et al. 2014). In the Norwegian study on mature CCF spruces near the timberline (Eikenes et al. 1995), basic density at stump height declined from an

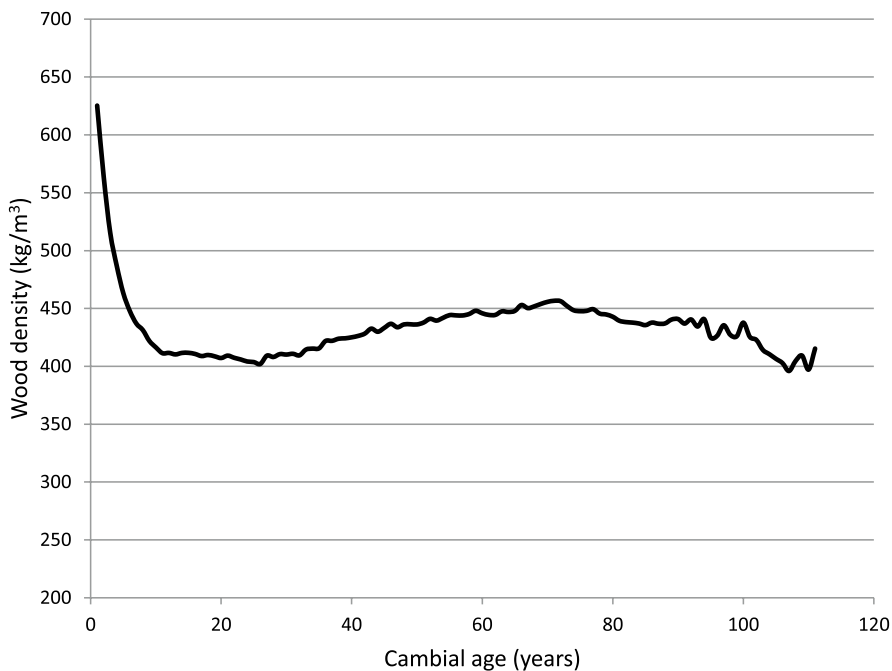


Fig. 9.4 Average wood density in Norway spruce trees in ERIKA selection stands at a height of 0.6 m from tree base, calculated with the model presented in Piispanen et al. (2014), applied to dominant trees ($d/D_{\text{dom}} = 1$), and with annual ring widths (ir) representing the average value by distance from the pith

initial average of 450 kg/m^3 near the pith to some 350 kg/m^3 near the bark. Further up the stem (20–80% tree height) the variations in density from pith to bark were very small.

9.2.3 Fiber Properties

Wood fibers particularly affect the quality of pulp, but also indirectly the strength and stiffness of sawn timber. A considerable proportion of the merchantable timber ends up as pulp, as the surface slabs of the sawlog stems and sawdust are directed to pulping.

The fiber properties in Norway spruce change because of tree growth and aging of the cambium. Both the fiber length and diameter tend to increase in response to the increasing mechanical stress and the hydraulic pressure required to move water to the crown. The analyses of the ERIKA data indicated that different fiber properties have differing responses to tree age and tree size. Pyörälä et al. (2022) found that, with respect to the cambial age, the Norway spruce fibers in the selection

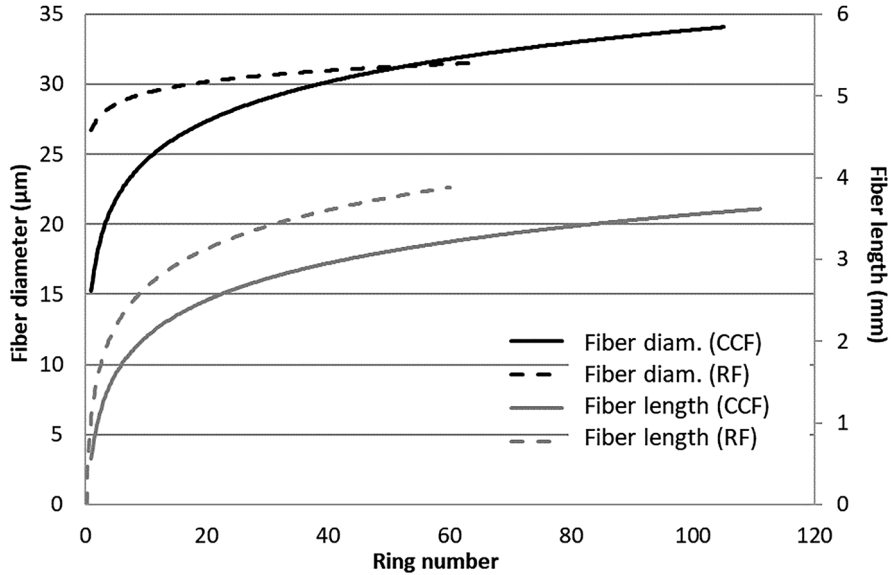


Fig. 9.5 Smoothed trends of fiber dimensions with respect to the age of the cambia in the ERIKA experimental data (CCF), and comparison data from RF materials. Data from Pyörälä et al. (2022)

stands lengthened more rapidly close to the pith than in RF stands, while the diameters of the fibers were more dependent on tree size (Fig. 9.5). As a result, Norway spruce grown under the selection system yielded a greater percentage of large fibers, which are associated with better pulp quality. This, too, was due to their specific growth patterns that lead to dominant mature spruces. These maintain relatively large and long crowns and require large-diameter earlywood fibers at stem base to sustain adequate water uptake, and long, thick-walled latewood fibers that contribute to the mechanical bearing capacity of the stem.

9.2.4 Traits and Quality of Sawn Goods

Expectations are high regarding the possibility of producing high-quality sawn timber in CCF. However, the quality of sawn goods is a result of several different factors. The complexity of the growth patterns in CCF can be expected to induce larger variation in the quality of sawn timber, both between and within individual trees.

In the study based on the ERIKA experiments with single-tree selection, 96 Norway spruces were processed into sawn timber at commercial sawmills, measured for quality traits, and graded according to the Nordic standard (Nordic Timber 1994) to grades ranging from A1 (flawless) down to A2–A4, B, C and D (reject) (Fig 9.6). The factors considered in the grading were the number, diameter and characteristics of knots, deformations (bow, cup, spring, and twist), the number and size of



Fig. 9.6 Demonstration of the quality grading in the ERIKA study. Photo Erkki Oksanen/Luke

pitch pockets and bark pockets, grain angle or distortion, proportion of compression wood, and the presence of resin wood, wetwood, firm rot or blue stain.

In the CCF trees, the most common reasons for quality downgrade in planks and boards of the butt logs were the large number of dead knots, compression wood, loose knots, and large diameter of the knots, which are typical for spruce wood irrespective of source. In the top logs, green knot diameter, wood twist and resin pockets caused the most problems, resulting in poorer quality grades (Pyörälä 2013; Piispanen et al. 2020).

Sawn timber from the selection stands was, on average, of similar quality to the lumber from the RF stands used for comparison, but the variation in quality was greater in the selection system; see Fig. 9.7 (Piispanen et al. 2020). The number of loose knots and the severity of twist often resulted in increased proportions of grade C (36%) compared with grade B (25%). The number of high-quality boards (grade A) was high in the selection trees (20%). Factors that caused boards to be downgraded to the lowest D category (19%) were often the proportion of compression wood and decay, and twist in the first boards from the pith (Piispanen et al. 2020).

In the butt logs of the selection trees, annual rings were very narrow close to the pith, but this was not correlated with deformations of boards (twist, bow, curved edge, and bottom) as previously suspected (Piispanen et al. 2020). On the contrary, the smaller amount of juvenile wood tended to reduce the amount of twist in boards close to the pith. In butt logs, twist was more evenly distributed, when the first boards were compared with the second and third boards from the pith. In even-aged spruces, twist is usually most severe in boards close to the pith. In uneven-aged trees, in the outermost boards, the presence of a high number of pin knots typically increased twist (Fig. 9.8).

Compression wood has also been expected to be a problem in single-tree selection, because the tree canopy positions change repeatedly due to recurring selection

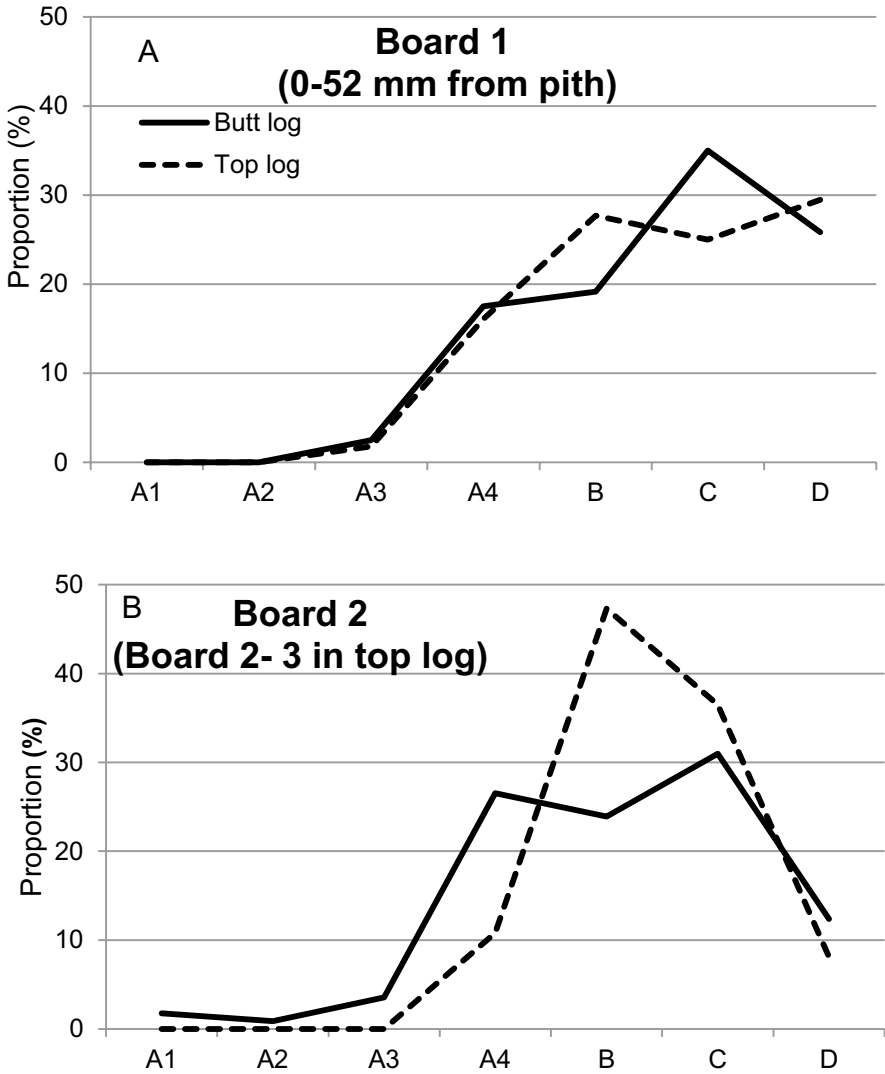


Fig. 9.7 Distribution of grades of the sawn boards (Nordic Timber 1994) obtained from the butt and top logs according to board location from the pith outwards—first board (0–52 mm from pith) to fifth board. Data from Piispanen et al. (2020)

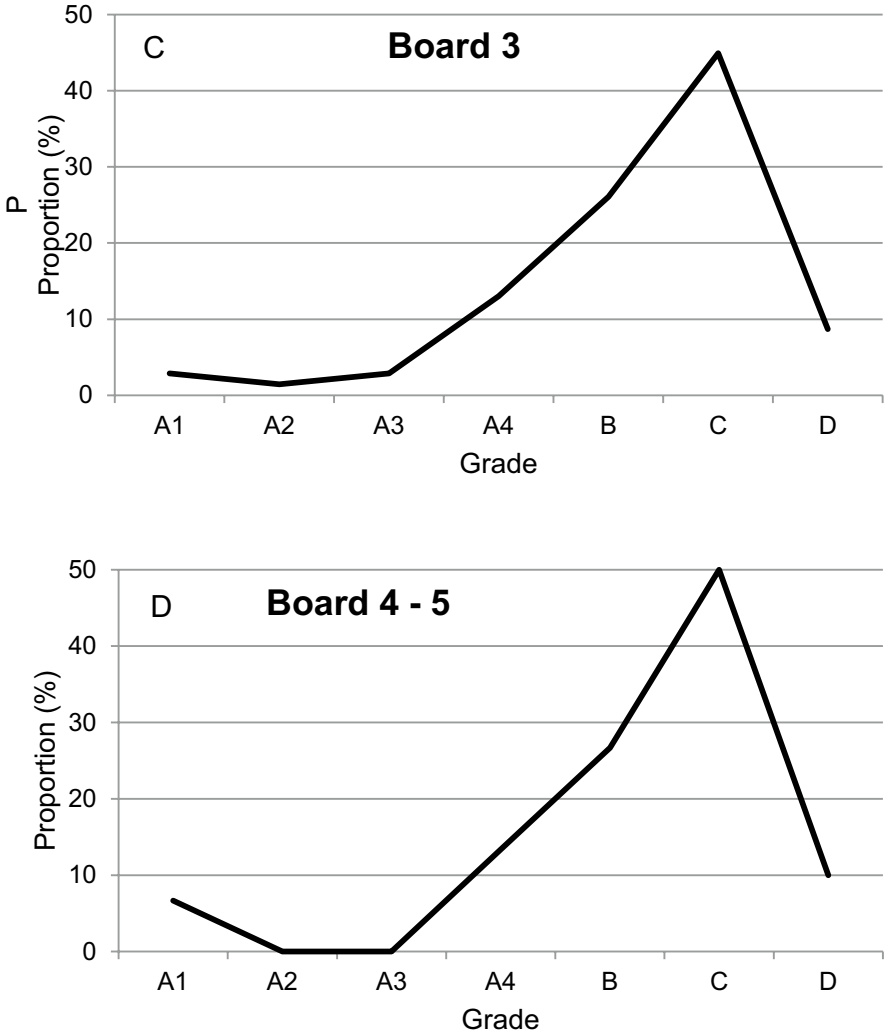


Fig. 9.7 (continued)

cuttings. In the edge trees of tree groups, asymmetrical crowns may develop, and the tensions can result in non-circular or slightly inclined tree stems, after the “supporting” trees are removed. However, the average proportion of compression wood in the ERIKA data was no larger than in southern Finnish lumber in general (Piispanen et al. 2020). The compression wood factor had no significant correlation to twist found in the ERIKA data.

Eikenes et al. (1995) also studied the strength of structural timber in Norway spruce selection stands using stress grading. They reported a mean bending strength of 42 MPa, which was higher than in their even-aged comparison materials. Twenty



Fig. 9.8 Severe twist in the board in the center among boards with little or no twist. Photo Erkki Oksanen/Luke

percent of the boards were visually strength-graded to the highest class T30, and 39% to the second class T24, according to the Norwegian standard NS 3470. Their findings showed that wood with very good strength properties can be produced in selection forests near the treeline in Norway.

9.3 Scots Pine Stands—From Shelterwood to Overstorey Retention

Uneven-aged structures are difficult to create and maintain with the shade-intolerant species of Scots pine, as already demonstrated by the Dauerwald selection system in northern Germany (Wiedemann 1925; Heinsdorf 1994; Helliwell 1997). Instead, a semi-continuous system based on natural regeneration with shelterwood (or seed-tree) cutting with subsequent overstorey retention seems to provide a more viable method for pine (see Chaps. 2 and 3). Part of its attractiveness in the contemporary CCF context could be the possibility to produce high-quality wood connected to a degree of continuity in large trees, with assumed benefits to biodiversity, amenity, and other ecosystem services. The long silvicultural experience with contemporary aspirations to increase structural complexity in pine stands (e.g., Der Wald in Sachsen 2005; Huth et al. 2022) in northern Germany is tangential and useful, together with basic research in Fennoscandia (see review by Vadla 1992 and Valkonen 2000; Valkonen et al. 2002).

Unfortunately, direct research on wood quality in such systems in the Nordic area is virtually lacking, apart from one that is clearly a pilot study (Kulmala 2016).

It seems safe to hypothesize that these kinds of management regimes can facilitate the production of high quality wood and wood products, especially compared to intensively managed pine stands in RF. Serious problems with abundant thick branches and a high proportion of juvenile wood associated with rapid initial tree growth have resulted from the large-scale planting of Scots pine on fertile sites with wide spacing patterns (Varmola 1996; Huuskonen 2008; Huuskonen et al. 2014).

The three principal elements linking the overstorey retention system with wood properties and quality are:

1. Wood quality in overstorey trees
2. Overstorey influence on wood quality in the understorey
3. Management for better wood quality in the understorey

When the best seed bearers or shelterwood trees of the old generation are retained for several decades on top of their previous rotation of 70–100 years, the additional growth that they accumulate tends to develop high-quality traits, producing wood quality in the highest categories. If high external quality is emphasized in the initial selection of trees to be retained, the stems are straight with few defects and free of branches up to a considerable height (Niemistö et al. 1993). The wood added with each annual ring will be knot-free up to a considerable height, which increases with time. The tree ring width tends to be moderate and rather constant, which is generally associated with good wood properties.

If the early development of the trees has been characterized by close spacing and the presence of overstorey trees, suppressing branch and stem diameter growth, wood quality can also be very good in the inner parts (towards the pith), especially in the lower stem parts (butt logs). On the other hand, the crown length in trees retained in relatively solitary positions does not contract, unlike trees in a closed canopy. In southern Finland, seed trees retained for 10–15 years had an average crown ratio of 0.42–0.51, depending on site fertility (Sarvas 1949). Comparable figures would be 0.30–0.33 in old unthinned natural stands and about 0.4 in mature managed stands (Hynynen 1995; Hynynen and Siipilehto 1996). The remaining branches become thicker, and the live crown zone will be associated with poorer quality of wood for sawn goods.

The results of the pilot study in Evo, southern Finland, supported these findings (Kulmala 2016). The study was conducted in one pine stand with an overstorey up to 180 years old and a managed understorey of 40–50 years of age. The overstorey consisted of large trees (diameter = 35–65 cm, dominant height 30 m) with a very high stem density (110 stems/ha). Gradual thinnings had been carried out during the stand's life cycle. The overstorey probably represented dimensions and traits that could be expected at the final stages of overstorey management corresponding to two normal rotations, but its density was far greater than what could be expected (e.g., 10 stems/ha, Valkonen 2020). The understorey had been gradually thinned to its current density of 2000 stems/ha. It had thrived surprisingly well underneath such a dense overstorey, with the largest individuals already achieving diameters of 20–25 cm (max 28 cm). The over- and understoreys were sampled separately,

applying stratification by diameter. The main results were obtained from sample logs taken at three heights (butt log 0–4 m, intermediate log 8–12 m, top log downwards from live crown) in the overstorey and at one or two heights in the understorey. The logs were sawn with a regular sawing pattern, and the sawn goods graded according to the Nordic standard (Nordic Timber 1994; see Sect. 9.2.4 for details of the system) and measured for strength according to the CSN EN 338 standard, based on the modulus of elasticity with an acoustic meter.

The results indicated that the sawn goods yielded from the overstorey pines were of exceptionally good quality. No less than 80% of boards sawn from the outer parts of the butt logs were assigned to the best A grade, with 50% in the A1 grade (not a single defect detected on a board). They originated mostly from the knot-free zone with consistent growth and no reaction wood or other traits that could have caused distortions in sawn goods. Their density was high for pine, 500–600 kg/m³. Planks sawn from the inner parts of butt logs were also high quality, with 70% in the A grade and 30% in A1. The boards were given very high grades in the EN 338 strength classification, with 80% in class 35 or above. Quality decreased upwards on the stem as the knot-free proportion decreased, but the grades were still very good for the intermediate logs.

Intense competition within the understorey and by the overstorey is a key factor influencing wood properties and quality from understorey trees in two-storey pine stands. It tends to reduce the diameter growth in both stems and branches, enhancing wood quality in terms of greater density and a smaller number and diameter of knots (Voegeli 1961; Ackzell and Lindgren 1992; Vadla 1992; Varmola 1996; Agestam et al. 1998). The proportion of poor-quality juvenile wood, which encompasses up to 10–20 first annual rings, becomes smaller with slower growth. The seed-tree and shelterwood methods facilitate the emergence and retention of relatively high stocking levels, with an additional contribution made by the overstorey trees. One of the very few studies addressing this concept in Scots pine stands was conducted by Valkonen et al. (2002) in sapling stage stands (dominant height 1–7 m) with overstoreys of large Scots pines (diameter 30–40 cm) retained for 8–18 years with 30–120 stems/ha. The overall branching (sum of cross-sectional areas of branches in the whorl with the thickest branch of the tree) was clearly suppressed in the vicinity of the overstorey trees (Fig. 9.9). However, there was less impact on the maximum branch diameter, considered a key trait (Varmola 1996). Both benefits were considered much smaller than what may be achieved by a successful site-species match and sufficient stocking level.

The high quality of sawn goods from the inner regions of the overstorey stems and from the understorey stems, and the very thin branches with a high degree of self-pruning in the current understorey trees, were further indications of the quality benefits of this management system.

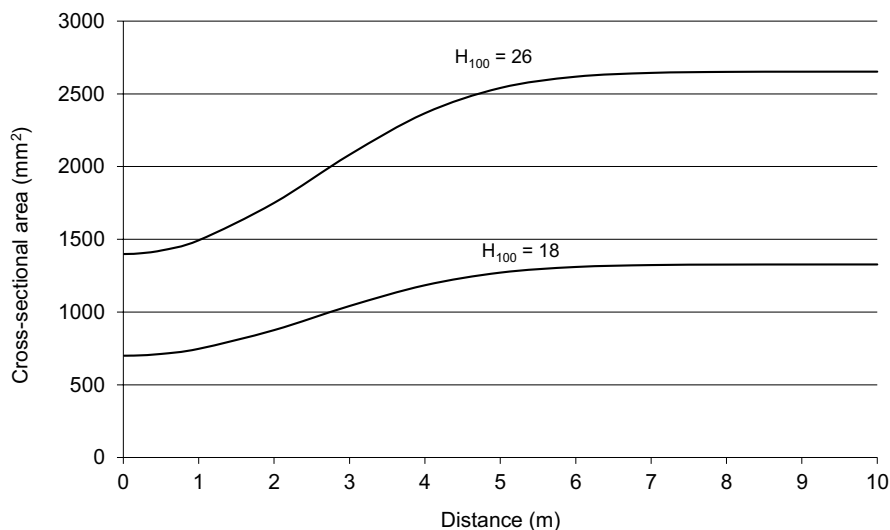


Fig. 9.9 Effect of overstorey trees on Scots pine saplings (height 5 m). Sum of branch cross-sectional area of three main whorls by distance from an overstorey pine tree with a diameter of 40 cm on a fertile ($H_{100} = 26$ m) and an infertile ($H_{100} = 18$ m) site. Data from Valkonen et al. (2002)

9.4 Knowledge Gaps

Few studies have considered the wood quality in CCF in Nordic countries. Some key wood properties, such as microfibril angle, remain undescribed in the literature, the geographical representativeness of the materials is still limited, and the length of the experiments still rather short compared to the lifespan of the trees. Few studies directly address either the shelterwood system with other species than Scots pine, or gap cutting for either Norway spruce or Scots pine.

If such studies are generally sparse, ones that would allow indisputable comparisons of the wood quality between CCF and RF are non-existent. Such comparisons are often problematic due to differences in sampling, measurement methods, and growth conditions. For example, Eikenes et al. (1995) stated that the selection stands used in their study were located near the timberline of spruce at high altitudes in the far north and had very low site indices (11–17 m), making comparisons with the main productive spruce forests with higher site indices rather difficult.

In the ERIKA studies on single-tree selection, five Swedish and two Finnish middle-aged RF stands were used as comparative data (see Piispanen et al. 2014). The RF material represented sawn timber from operational harvests, where poor-quality logs are usually removed by logistics already in the forest or at least before sawing. In contrast, logs from the ERIKA sample trees were not preselected before sawing, and the boards were graded with no consideration of external characteristics of the log that would have resulted in an advance rejection in an industrial process. Unsurprisingly, direct data-based evaluation was possible for only a very few

features, and results from previous studies or literature were used on case-by-case basis.

Despite these challenges, the presented research provides valuable insights about wood properties and quality in forests managed with the CCF regimes, and has revealed the key differences to those managed with RF. This allows logical deductions of some potential outcomes.

9.5 Conclusions

Based on current knowledge, the key determinant of wood properties and quality in spruce selection stands is the extremely slow juvenile growth occurring during the early suppression phase. Accompanied by the relatively rapid growth rates of the mature trees in dominant positions, the proportion of juvenile wood remains relatively small in the stems, which improves the mean density and other traits in the merchantable stems.

The quality of sawn timber in the Norway spruces in the selection system did not differ noticeably from that in RF. However, Eikenes et al. (1995) found very good strength properties in Norway spruce selection forests near the timberline in Norway. The shelterwood method facilitates the production of Scots pine timber with very high quality grades.

The fiber properties in the selection stands were slightly better suited to pulp production than those in RF. The large crowns in dominant trees resulted in long and wide fibers in mature wood, i.e., in the surfaces of sawlogs, much of which ends up in pulping as side-streams of sawing.

Besides the superiority or inferiority of the wood for any particular purpose, a more important observation arising from the wood quality studies in CCF is how the rate and timing of the wood formation processes differ under different regimes. The research results offer further confirmation of the findings that Norway spruce can recover and rejuvenate after decades of suppression, and that the old trees in selection stands can maintain relatively large crowns in the abundant canopy space, boosting the rates of stem diameter growth to levels greater than those in trees with similar ages in the closed-canopy RF. The high growth rates in the old spruces in the selection stands were associated with relatively high ring densities and large tracheids. Similarly, the very old Scots pines in the overstoreys of the shelterwood system (up to 180 years old) retained good volume growth with their large live crowns, and produced high-grade timber in their stem base.

The lifespan of an individual tree in CCF is generally longer than in RF. Slow growth occurs in the suppressed, juvenile trees, but does not necessarily lead to a poor financial outcome. Having assumed an uneven-aged structure, the reserve of regeneration and suppressed trees ensures a steady supply of fast-growing mature trees to the relatively sparse upper canopy when larger trees are repeatedly removed. However, the transition period of an even-aged forest into a balanced uneven-aged

structure will cause financial losses, due to the delayed harvests in the upper layers and the establishment of the sapling reserve.

The slower juvenile growth and longer rotation of individual trees is currently not financially compensated for by the increase in wood density, or tracheid quality, due to the volume-focused wood markets that do not consider wood quality. In the future, possible premiums or compensation paid for wood quality or carbon-binding potential could make CCF more attractive on sites with potential for prolonging the lifespans of the dominant trees. The main risk, especially for Norway spruces in CCF, is the root rot caused by *Heterobasidion annosum*, which can develop into a major problem in spruce-dominated forests, causing big financial losses. The main means for mitigating the risks of infection are careful logging and the restriction of harvests to the cool season when there are no spores in the air, a topic discussed in more detail elsewhere in this book.

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