# Quality and Bending Properties of Sawn Timber from Commercial Thinnings of Scots Pine (*Pinus sylvestris* L.)

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*Abstract*

In this study, the visual characteristics and static bending properties of Scots pine (*Pinus sylvestris* L.) sawn timber were determined using the material collected from thinning and final-felling stands in eastern Finland. The quality of boards was assessed based on the Nordic visual strength grading rules for timber, and the bending strength, and modulus of elasticity were determined according to the European standard test EN 408. Based on the visual strength grading, the majority of boards met the requirements of the visual grade T1, whereas the highest grade T3 was achieved by less than 10% of the boards. The bending strength and modulus of elasticity of sawn timber from the first thinnings were 42.0 MPa and 10.2 GPa, and those from the second thinnings 52.6 MPa and 12.8.GPa, respectively. The distribution of theoretic strength classes indicated a strong focus on C30 or higher for the material from the second thinnings, whereas the strength classes of C24 or lower were most common for the material from the first thinnings. Regarding the bending properties, the sawn timber from the butt logs of the first-thinning trees was comparable with that of the middle or top logs from later cuttings. The strength and modulus of elasticity of the first-thinning material were relatively low, whereas the Scots pine sawn timber from the second commercial thinnings may be comparable with that from the current final fellings.

**Key words:** bending strength, modulus of elasticity, visual strength grading, *Pinus sylvestris* L., sawn timber, structural products, thinning.

## Introduction

Scots pine (*Pinus sylvestris* L.) is increasingly used for structural wood products, such as sawn timber and glued laminated timber in columns, beams, roof trusses, and joists. In construction uses, timber must meet certain requirements of strength, stiffness and density, as well as dimensional and shape stability, and have an even moisture content (Madsen 1992, Glos 1995, Hoffmeyer 1995, Johansson 2003). To guarantee the required level of structural safety for the users, the properties of timber must be determined reliably. Grading into strength classes, which express the load-carrying capacity of the products, allows the allocation of the pieces of sawn timber for the most suitable end-use applications.

Bending is the most important mode of stress for structural timber. Accordingly, the strength classes of sawn timber are determined by the density and the ability of a member to resist bending, that is, bending strength and stiffness (Desch 1981, Finnish Standards Association 2010, Hanhijärvi et al. 2005). The bending properties are easy to measure, although, compared to other standard tests, more complicated to analyse as bending results in a combination of three-dimensional tension, compression, and shear strains (Bodig and Jayne 1982). In addition to defects, density, moisture content and temperature of wood, and loading time affect the bending properties of sawn timber (Desch 1981).

The significance of thinning forests as a timber resource, and the utilisation of thinning wood in mechanical wood processing for construction timber and further-processed building products, are increasing. In Finland, for example, according to the calculations of sustainable recovery of industrial roundwood and energywood based on the 11$^{th}$ National Forest Inventory (NFI), the proportion of merchantable timber harvested in thinning forests is expected to increase from 26% to 36% of the total recovery during the period 2010–2039 (Salminen 2014). Nowadays, *circa* 60% of the forest land area is covered by young and advanced thinning stands; the change in the age structure of the Finnish forests towards the younger development classes is due to the intensive draining of peatlands in the 1960s and 1970s, and the accelerated regeneration of old-growth forests since the 1950s. In 2012, the first thinnings were carried out on 190,300 hectares and other thinnings on 288,500 hectares, whereas a decade earlier the coverage was 175,000 hectares and 162,200 hectares, respectively (Finnish Forest Research Institute 2013). During the current 10-year period, the recommended area of first thinnings is 2.2 times the area carried out during the previous period (Packalen et al. 2015).

Cuttings in thinning forests produce mainly pulpwood, although the use of thinning wood as forest energy is also increasing. The yield of logs and small-sized logs from thinning forest is limited, concentrating rather on the later thinnings than on the first thinnings. The dimensions of small-sized logs are those between the logs and pulpwood, thus varying notably depending on the receiving sawmill. For instance, the minimum diameter of 10 cm and length of 28 dm have been accepted for small-sized logs in Finland.

From the thinnings in 2012, the volume of roundwood trade from standing sales was 1,236,000 $m^3$ for pine logs and small-sized logs, and 842,000 $m^3$ for spruce logs and small-sized logs (Finnish Forest Research Institute 2013). Thus thinnings produced 26% of the total volume of pine logs, and 14% of the volume of spruce logs from the standing sales of private forests. The Finnish wood products industry utilises approximately two million cubic metres of domestic small-sized logs annually (Finnish Forest Research Institute 2013). In the pine sawmills, the proportion of small-sized logs of the total wood consumption is approximately 16 %, and in the spruce sawmills 5-6 % (Finnish Forest Research Institute 2013). Sawn timber from small-sized logs may be used in the products requiring high visual and technical quality, such as in construction and in furniture, as well as in the non-visible or low-quality products. In yard equipment, small-sized round timber is used, for instance, as poles and in fences.

The aim of this study was to determine the visual quality, bending strength (MOR), and modulus of elasticity (MOE) of Scots pine (*Pinus sylvestris* L.) sawn timber from commercial thinnings, and, furthermore, to study the effects of different stand and tree characteristics on the strength properties. As a reference, sawn timber from final fellings was studied.

## Material and Methods

### *Material*

The data for the study were collected from twelve Scots pine dominated stands in the North Karelia region in eastern Finland. The forests were young and advanced thinning stands, and mature stands, here described according to their silvicultural status as first-thinning, second-thinning, and final-felling stands, respectively (Table 1). The stands were located on mineral soils and drained peatlands (transformed types), due to which the variation in soil fertility was notable, from the *Myrtillus* type to the dwarf-shrub transformed type (Cajander 1949, Paavilainen and Päivänen 1995). In each stand, the basic properties, such as breast-height diameter (dbh), height (h), and branch limits, were measured of *circa* 40 trees from a sample plot with the minimum area of 200 $m^2$. Ten sample trees were felled from each stand, representing the dbh-distributions of the trees on the stands. From a sample tree, at least one 2.5-m-long log with the minimum diameter of 8 cm (over bark) had to be obtained.

The felled sample trees were cut into bolts down to the top diameter of 8 cm. In cross-cutting, no commercial bucking instructions were followed. From the base of each log, a 3-cm-thick disc was sawn for determining the wood properties, such as growth ring width. The stem part up to the height of 4 m (±0.5 m) was classified as the butt log section, the stem part from 4 to 8 m (±0.5 m) as the middle log section, and the rest of the stem down to the minimum top diameter as the top log section. From the first thinnings, 48 butt logs, 28 middle logs, and 6 top logs were obtained, and from the second thinnings, 65 butt logs, 52 middle logs, and 56 top logs. In addition, 39 butt logs, 39 middle logs, and 103 top logs were obtained from the final fellings (Figure 1).

The logs were sawn through-and-through, and edged into boards with the dimensions of 50×50 mm, 50×75 mm, and 50×100 mm (Figure 2). Due to the small size of the logs, most of them did not enable more than one board from both sides outwards from the pith; thus the majority of boards represented the centre yield. The 50×100-mm boards were most often obtained from the final fellings and the butt logs. The distributions of the smaller boards were relatively even between the stand types and log sections. The boards were stored outdoors in sticker-stacks sheltered until the measurement of their quality.

**Table 1.** Characteristics of study stands and sample trees

| Stand number | Stand type | Site type | Stems/ha | Age, yrs | Dbh, cm | h, m |
|---|---|---|---|---|---|---|
| 1 | First thinning | *Myrtillus* type | 1750 | 30 | 13.3 | 11.9 |
| 2 | First thinning | *Myrtillus* type | 1850 | 36 | 14.3 | 13.2 |
| 3 | First thinning | *Vaccinium* type | 2250 | 37 | 12.2 | 12.4 |
| 4 | First thinning | *Vaccinium* type | 2350 | 50 | 13.6 | 15.4 |
| 5 | First thinning | *Vaccinium vitis-idaea* transformed type | 1343 | 35 | 12.2 | 11.3 |
| 6 | First thinning | *Vaccinium vitis-idaea* transformed type | 1364 | 50 | 15.7 | 15.5 |
| 7 | Second thinning | *Myrtillus* type | 1500 | 68 | 22.4 | 21.3 |
| 8 | Second thinning | *Vaccinium* type | 1100 | 66 | 20.9 | 21.6 |
| 9 | Second thinning | *Calluna* type | 1600 | 70 | 14.6 | 15.4 |
| 10 | Second thinning | Dwarf-shrub transformed type | 1833 | 90 | 15.5 | 14.6 |
| 11 | Final felling | *Myrtillus* type | 375 | 85 | 26.3 | 23.0 |
| 12 | Final felling | *Myrtillus* type | 500 | 75 | 30.4 | 27.4 |

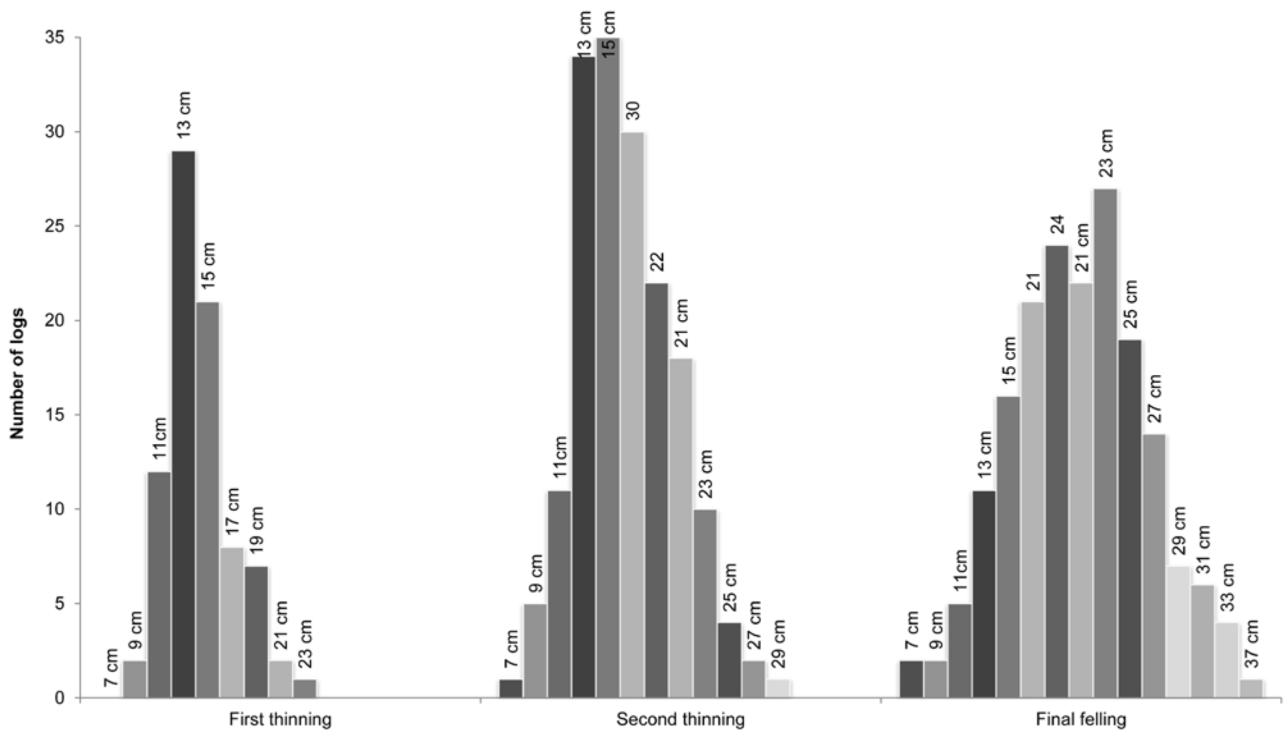


**Figure 1.** Top diameter distributions of the logs, according to the stand type

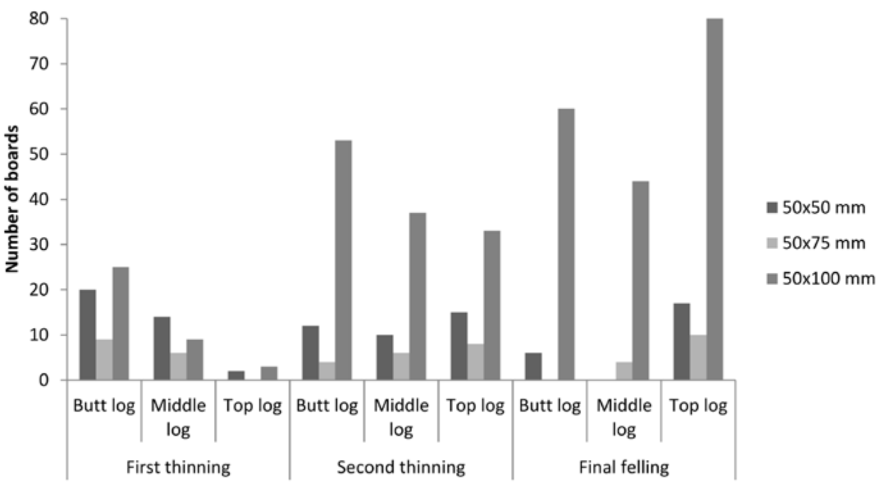


**Figure 2.** Number of boards, according to their dimensions, log sections, and stand types

***Methods***

Selected visual properties of the boards were determined in order to characterise their overall quality as potential commercial wood products for construction. Here, the size, location, and number of knots, distortions, slope of grain, wane, shakes, resin and bark pockets, scars, top breaks, reaction wood, and decay were taken into account. The degrees of distortions, bow, spring, cup, and twist were measured as the largest deviation from the plane normal (Finnish Standards Association 2010), and the slope of grain as the largest deviation of the grain angle, both over a one-metre range in the middle of the board. The length and width of shakes, resin and bark pockets, scars, top breaks, reaction wood, and decay were measured, and the occurrence of blue stain was recorded. Growth ring width was determined microscopically from the discs sawn from the base of each log; the mean calculated for the discs represented the average growth ring width of the boards between the upper and the lower disc.

Knots were classified as sound, dead, bark-ringed, rotten, loose, encased, spike, vertical, and pin knots, and their size and location in the boards were measured. Spike knots were classified as edge knots and vertical knots as top breaks. Knot sum was determined on a range equal to the width of the board. The weakest point of each board was determined visually, and its distance from the butt-end of the board was measured.

Based on the knots and other defects, the boards were graded visually into grades T0–T3, in accordance with the Nordic visual strength grading rules (Finnish Standards Association 2010). The bending strengths in the grades T3, T2, T1, and T0 are 30 MPa, 24 MPa, 18 MPa, and 14 MPa, respectively. Hence, T3 corresponds roughly to the strength class of C30, T2 to C24, T1 to C18, and T0 to C14.

The boards were conditioned in a standard environment (20 ± 2°C, RH 65 ± 5%) to achieve a constant moisture content (MC). The MC was measured from each board with an electronic moisture meter. The MC of every tenth board was determined using the oven-dry method, according to which the true MC of the boards at the test conditions was on average 13%. The measured MC was approximately 1.3 percentage units lower than that given by the oven-dry method. Thus, the MC (%) of each board at the time of test was adjusted by means of the following linear regression model:

$$MC_{adjusted} = 5.65 + 0.628 \times MC_{measured}, \qquad (1)$$

The air-dry density ($\rho_{12}$, kg/m$^3$) of each board was determined after weighing, and measuring its dimensions. The density values were adjusted to the MC 12 % according to the standard methods (Finnish Standards Association 2010).

The tests of bending strength and local modulus of elasticity were carried out as edgewise four-point bending, according to the standard EN 408 (Finnish Standards Association 2003). When possible, the visually determined weakest point of the board was placed centred between the loading points, and tensile stress during the test was applied on the weaker one of the edges. Bending strength (MOR) ($f_m$, Mpa = N/mm$^2$) and modulus of elasticity (MOE) ($E_m$, Gpa = kN/mm$^2$) were calculated as follows (Finnish Standards Association 2003):

$$f_m = \frac{aF_{max}}{2W}, \qquad (2)$$

$$E_m = \frac{al_1^2(F_2 - F_1)}{16l(w_2 - w_1)}, \qquad (3)$$

where

$a$ = distance between the loading position and the nearest support, mm,

$F_{max}$ = maximum load, N,

$W$ = section modulus, mm$^3$,

$l_1$ = span, mm,

$F_2$–$F_1$ = increment of load, N,

$I$ = second moment of area (mm$^4$), *and*

$w^2$–$w^1$ = increment of deformation (mm).

The MOR and MOE were adjusted to the moisture content of 12% using the equations (Boström 1994):

$$f_{m,12} = \frac{f_\omega}{1+00295(12-\omega)}, \qquad (4)$$

$$f_{12} = \frac{E_\omega}{1+00143(12-\omega)}, \qquad (5)$$

where

$f_{m,12}$ = bending strength at MC 12%,

$E_{12}$ = modulus of elasticity at MC 12%,

$\omega$ = MC, %, $f_\omega$, *and*

$E_\omega$ = bending strength and modulus of elasticity at the MC of ω%.

The characteristic values of strength, modulus of elasticity, and density were calculated for each stratum as stated in the standard SFS-EN 384 (Finnish Standards Association 2010). The theoretic strength class of each unsorted stratum was determined based on the limiting values given in the standard SFS-EN 338 (Finnish Standards Association 2010).

The linear mixed model approach was used to study the sources of variation at different levels in bending strength and modulus of elasticity of sawn timber. The linear mixed models with 3-level hierarchical random effects were fitted for MOR and MOE, using IBM SPSS Statistics Software. Factors such as the stand type (first thinning, second thinning, final felling), site type (*Myrtillus* type, *Vaccinium* type, *Calluna* type, *Vaccinium vitis-idaea* transformed type, dwarf-shrub transformed type), log section (butt log, middle log, top log), board dimension (50×100 mm, 50×75 mm, 50×50 mm), wood density, growth ring width, and tree age were entered in the LMMs as fixed effects. The pairwise interactions of the fixed factors were tested, as were the interactions among 3 independent factors. The stand, tree, and log were included in the models as hierarchical random factors. The model assumptions of the final models were checked using residual plots.

In the best fit model for MOR, the stand type, site type, log section, board dimension, wood density, and growth ring width were entered as fixed factors (Equation 6). The interaction between site type and wood density was noted significant, whereas the interactions among 3 independent fixed factors were insignificant.

$$MOR = b_0 + site + type + section + dim + \\ + b_1 density + + b_{site} density + b_2 grw + stand + \\ + tree + log + \varepsilon, \qquad (6)$$

where
$MOR$ = bending strength of a board,
$b_0$ = intercept,
$site$ = forest site type,
$type$ = development class of the stand,
$section$ = log section,
$dim$ = board dimension,
$b_1$ = regression coefficient for density,
$b_{site}$ = difference between $b_1$ and the regression coefficient for a site,
$density$ = basic density,
$b_2$ = regression coefficient for growth ring width,
$grw$ = growth ring width,
$stand$ = forest study stand (random effect),
$tree$ = sample tree within a stand (random effect),
$log$ = individual log cut from a sample tree (random effect),
$\varepsilon$ = error term.

In the best fit model for MOE, the stand type, wood density, and knot sum were included as fixed factors (Equation 7). No significant interactions between fixed factors were noted.

$$MOE = b_0 + type + b_1 density + b_2 knot + \\ + stand + tree + log + \varepsilon, \quad (7)$$

where
$MOE$ = modulus of elasticity of a board,
$b_0$ = intercept,
$type$ = development class of the stand,
$b_1$ = regression coefficient for density,
$density$ = basic density,
$b_2$ = regression coefficient for knot sum,
$knot$ = knot sum,
$stand$ = forest study stand (random effect),
$tree$ = sample tree (random effect),
$log$ = individual log cut from a sample tree (random effect),
$\varepsilon$ = error term.

## Results

### *Quality and visual strength grading of sawn timber*

In the boards from thinnings, the largest knot diameters were smaller than 30 mm (Table 2). The maximum diameters of sound and dead face and edge knots, bark-ringed knots, and the knot sum varied statistically significantly among the stand types, being, in general, larger in the final fellings than in the other stand types. The knot sum was smallest in the boards from the second thinnings. When comparing the sizes of dry, rotten, and bark-ringed knots, they were noted to be the smallest in the butt logs. The variation of knot diameters between the board dimensions was smaller in the final fellings than in the other stand types. Generally, the knot diameters increased along with the board dimensions.

Concerning the deformations, bow was more common and, according to the analysis of variance, somewhat larger in size in sawn timber from the first thinnings than from the second thinnings or the final fellings (Figure 2). In addition, bow was larger in the final felling boards than in the second-thinning boards. The most common defects noted in the boards were slope of grain, top breaks, and drying shakes. Slope of grain was found in almost every board, and it was somewhat steeper in the final fellings than in the first thinnings or the second thinnings (Figure 3). Top breaks were longer in the boards from the first thinnings than in those from the other stand types, but no statistically significant differences among the stand types were found. Drying shakes, in turn, were longer and more common than the other types of shake in all stand types, and found in about 50% of the boards.

According to the Nordic visual strength grading rules for sawn timber, the proportion of boards in the highest grade T3 was equal in the second thinnings and in final fellings, and somewhat lower in the first thinnings (Figure 4). However, the proportion of boards allocated to the two best grades, T2 and T3, was markedly higher in the first thinnings than in the later cuttings. Most of the boards met the requirements of the grade T1, whereas the proportion

**Table 2.** The diameters, types, and locations of the largest knots, and the knot sums, according to the stand type and board dimension

| Stand type | Board dimensions | Largest knot size/diameter/type/location | Knot sum, mm |
|---|---|---|---|
| First thinning | 50×50 mm (n=36) | 26 mm/sound/edge | 49 |
| | 50×75 mm (n=15) | 22 mm/sound/face | 54 |
| | 50×100 mm (n=37) | 29 mm/rotten/face | 54 |
| Second thinning | 50×50 mm (n=37) | 23 mm/sound/edge | 44 |
| | 50×75 mm (n=18) | 24 mm/sound/face | 46 |
| | 50×100 mm (n=123) | 26 mm/sound/face | 41 |
| Final felling | 50×50 mm (n=23) | 44 mm/dead/edge | 52 |
| | 50×75 mm (n=14) | 39 mm/bark-ringed/edge | 51 |
| | 50×100 mm (n=184) | 29 mm/sound/face | 54 |

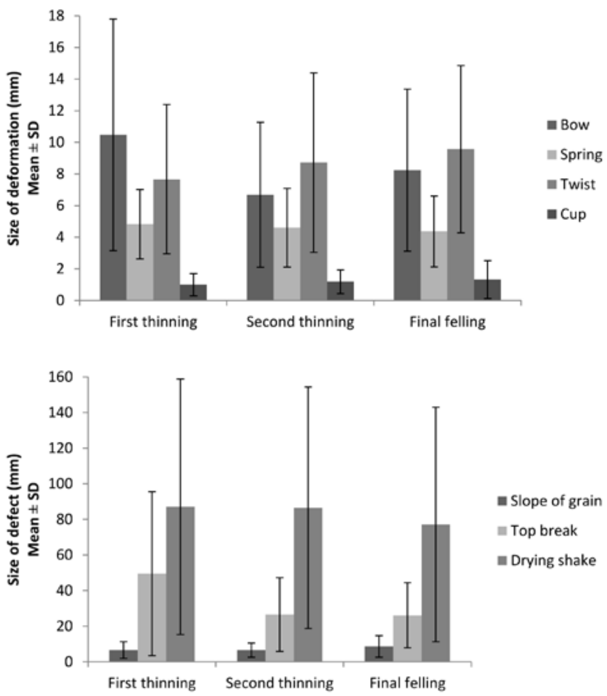


**Figure 3.** The sizes of deformations and defects (mm), according to the stand type

of boards allocated to the lowest grade T0 was at the same level in the first thinnings and in final fellings, but lower in the second thinnings. The 50×50-mm boards were mostly graded to T2, and those with the larger dimensions to T1. The visual strength grades of the smallest pieces of sawn timber were determined mainly by slope of grain, ring shake, and top break, whereas the strength grades of larger sawn timber dimensions were most affected by the face and edge knots, and slope of grain.

***Density, bending strength, and modulus of elasticity***

Comparing the stand types, the first thinnings produced sawn timber with the lowest density, MOR, and MOE (Table 3). The properties of sawn timber from the second thinnings were somewhat better than those of the sawn timber from the final fellings. The variation of bending properties was notable; calculated from the entire data, the coefficients of variation (CV) of MOR and MOE were 36% and 27%, respectively.

Density, MOR, and MOE decreased from the butt log section to the top log section. Roughly, the butt log section of the first-thinning trees corresponded to the middle and top log sections of the second-thinning and final-felling trees. The variation in the studied properties, especially in density, was generally higher in the butt log section than in the upper log sections.

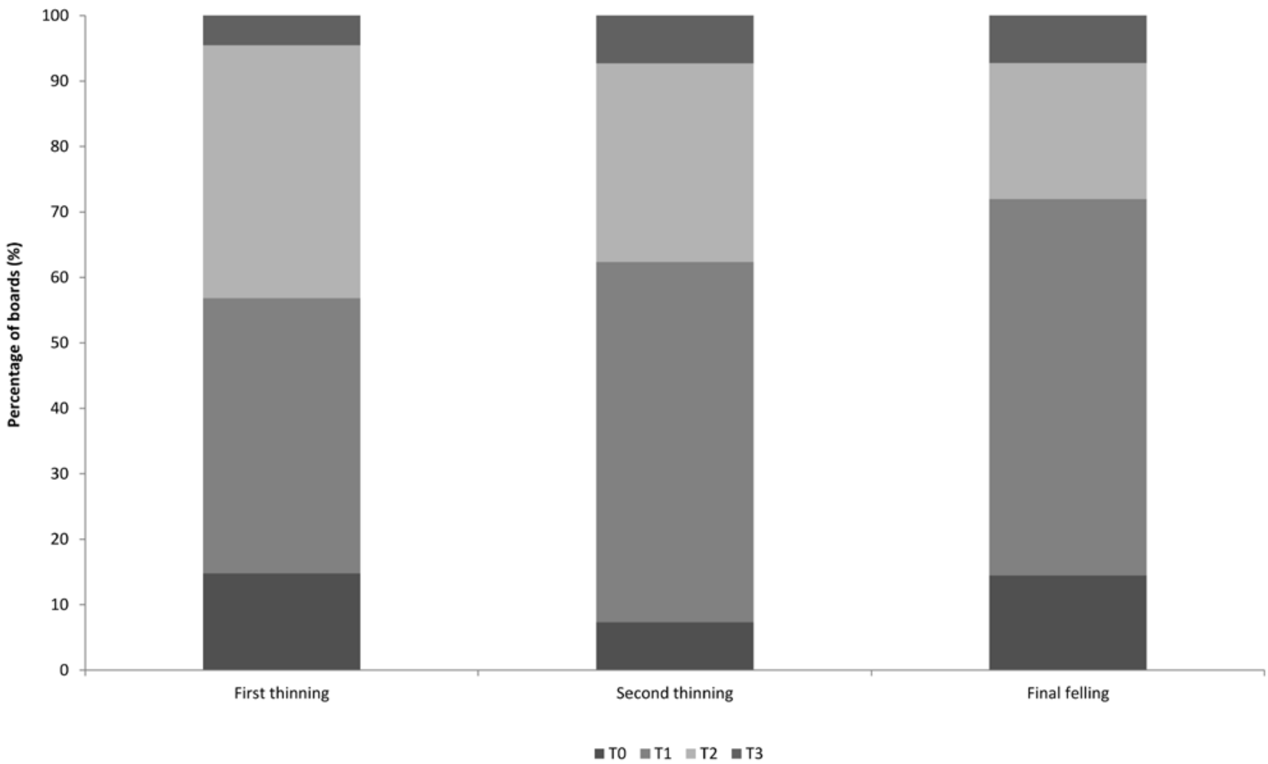


**Figure 4.** Visual strength grade distributions of the pieces of sawn timber, according to the stand type

The structure of study material was uneven among the site types, the majority of boards originating in *Myrtillus* type forests (Table 4). Based on the arithmetic values, both MOR and MOE were highest on *Calluna* type, along with the highest wood density.

Density, MOR, and MOE were highest in the largest boards (50×100 mm), which typically represented the centre yield of butt logs (Table 5). Density and MOE of the 50×75-mm boards were higher than those of the 50×50-mm boards, whereas MOR in the 50×50-mm boards was at the same level with that of the 50×100-mm boards.

In the linear mixed model analysis for MOR, the stand type was entered as a fixed factor, despite it being statistically insignificant ($p$ = 0.493) (Equation 6). Other fixed factors in the model were the site type ($p$ = 0.002), log section ($p$ = 0.002), board dimension ($p$ = 0.044), wood density ($p \leq 0.001$), growth ring width ($p \leq 0.001$), and the interaction term of the site type and wood density ($p$ = 0.002).

Based on the estimated marginal means (EMMEANS), the bending strength of boards varied according to the forest development classes, i.e. stand types, be-

**Table 3.** Means, standard deviations, and the 5th percentiles of density ($\rho_{12}$), MOR ($f_{m,12}$), and MOE ($E_{12}$), according to stand type and log section

| | $\rho_{12}$, kg/m³ | | | $f_{m,12}$, MPa | | | $E_{12}$, GPa | | |
|---|---|---|---|---|---|---|---|---|---|
| Stand type<br>Log section | Mean | Std. dev. | 5th percentile | Mean | Std. dev. | 5th percentile | Mean | Std. dev. | 5th percentile |
| First thinning | | | | | | | | | |
| Butt log (n=54) | 478.1 | 43.6 | 411.7 | 44.8 | 17.2 | 21.1 | 10.8 | 3.2 | 6.2 |
| Middle log (n=29) | 452.1 | 26.9 | 404.3 | 38.6 | 13.5 | 20.1 | 9.3 | 2.5 | 4.9 |
| Top log (n=5) | 433.7 | 34.6 | n/a | 32.3 | 13.4 | n/a | 8.3 | 2.8 | n/a |
| Total (n=88) | 467.0 | 40.8 | 398.9 | 42.0 | 16.1 | 21.4 | 10.2 | 3.0 | 5.5 |
| Second thinning | | | | | | | | | |
| Butt log (n=69) | 531.2 | 53.1 | 450.9 | 64.2 | 12.5 | 44.0 | 14.8 | 2.5 | 9.9 |
| Middle log (n=53) | 482.2 | 37.4 | 430.3 | 48.8 | 11.9 | 30.7 | 12.3 | 2.3 | 8.2 |
| Top log (n=56) | 462.7 | 34.5 | 410.1 | 41.8 | 12.9 | 21.9 | 10.9 | 2.7 | 7.3 |
| Total (n=178) | 495.0 | 52.5 | 423.7 | 52.6 | 15.7 | 28.7 | 12.8 | 3.0 | 7.7 |
| Final felling | | | | | | | | | |
| Butt log (n=66) | 514.3 | 44.2 | 434.7 | 56.1 | 16.5 | 25.9 | 13.5 | 2.9 | 8.6 |
| Middle log (n=48) | 465.7 | 33.3 | 411.9 | 39.7 | 14.6 | 19.6 | 11.7 | 2.6 | 7.2 |
| Top log (n=107) | 460.1 | 24.2 | 413.9 | 36.4 | 9.8 | 20.6 | 10.2 | 2.5 | 6.8 |
| Total (n=221) | 477.5 | 41.0 | 418.6 | 43.0 | 15.7 | 21.6 | 11.5 | 3.0 | 7.2 |
| All (n=487) | 482.0 | 46.6 | 418.2 | 46.3 | 16.5 | 23.4 | 11.7 | 3.2 | 7.1 |

**Table 4.** Means, standard deviations, and the 5th percentiles of density ($\rho_{12}$), MOR ($f_{m,12}$), and MOE ($E_{12}$), according to site type

| | $\rho_{12}$, kg/m³ | | | $f_{m,12}$, MPa | | | $E_{12}$, GPa | | |
|---|---|---|---|---|---|---|---|---|---|
| Site type | Mean | Std. dev. | 5th percentile | Mean | Std. dev. | 5th percentile | Mean | Std. dev. | 5th percentile |
| *Myrtillus* type (n=308) | 474.1 | 41.7 | 415.6 | 42.7 | 15.4 | 21.3 | 11.4 | 3.1 | 6.8 |
| *Vaccinium* type (n=96) | 491.1 | 45.7 | 423.7 | 52.8 | 15.6 | 29.5 | 12.5 | 3.2 | 7.4 |
| *Calluna* type (n=25) | 546.5 | 61.1 | 437.8 | 65.8 | 12.9 | 41.7 | 14.9 | 2.5 | 9.7 |
| *Vaccinium vitis-idaea* transformed type (n=34) | 465.7 | 37.2 | 397.0 | 42.0 | 14.8 | 23.5 | 10.4 | 2.8 | 6.1 |
| Dwarf-shrub transformed type (n=24) | 503.7 | 39.5 | 456.5 | 52.4 | 16.2 | 29.1 | 12.1 | 3.0 | 6.7 |

**Table 5.** Means, standard deviations, and the 5th percentiles of density ($\rho_{12}$), MOR ($f_{m,12}$), and MOE ($E_{12}$), according to board dimension

| | $\rho_{12}$, kg/m³ | | | $f_{m,12}$, MPa | | | $E_{12}$, GPa | | |
|---|---|---|---|---|---|---|---|---|---|
| Board dimension | Mean | Std. dev. | 5th percentile | Mean | Std. dev. | 5th percentile | Mean | Std. dev. | 5th percentile |
| 50×50 (n=38) | 473.4 | 44.8 | 405.1 | 46.1 | 17.2 | 21.9 | 10.1 | 3.3 | 5.5 |
| 50×75 (n=13) | 476.0 | 44.5 | 418.5 | 41.1 | 13.7 | 21.8 | 11.0 | 2.8 | 7.0 |
| 50×100 (n=138) | 485.3 | 47.1 | 424.4 | 47.1 | 16.5 | 23.9 | 12.3 | 3.0 | 7.9 |

ing the highest in the boards from the second thinnings, whereas the strength levels of the first-thinning and final-felling boards were relatively even. The pairwise comparisons between site types indicated markedly higher MOR of boards originating in the *Calluna* type mineral soils. The *Calluna* type forests were included in the study material from the second thinnings only. However, the interaction of stand type and site type was noted insignificant in the LMM. A strong positive association between density and MOR was noted on all site types. The wood density as an individual fixed factor had a positive effect on bending strength (Figure 5). Changes in density and growth ring width affected MOR most strongly in the first thinnings. With the low level of wood density, MOR was somewhat higher in the second thinnings than in the other stand types (Figure 5). As expected, the pairwise comparisons showed the MOR to be markedly higher in the butt logs than in the upper parts of the stem. Instead, the difference in MOR between the middle and top logs was statistically insignificant. The EMMEANS for different board dimensions strongly indicated lower MOR values for the 50×75-mm boards than for the other dimensions. The bending strength decreased with increasing growth ring width, and the highest MOR values were noted for trees with maximum 1.7-mm average growth ring width (Figure 5). Again, the growth ring width had the strongest effect on the MOR of first-thinning boards.

The stand type was entered as a fixed factor in the linear mixed model for MOE, even though it was found statistically insignificant ($p$ = 0.065) (Equation 7). The other fixed factors included in the model were the wood density ($p \leq 0.001$) and the knot sum ($p \leq 0.001$).

The estimated marginal means for the stand types indicated the highest modulus of elasticity in the boards from the second thinnings, and the lowest one in those from the final fellings. Expectedly, the modulus of elas-

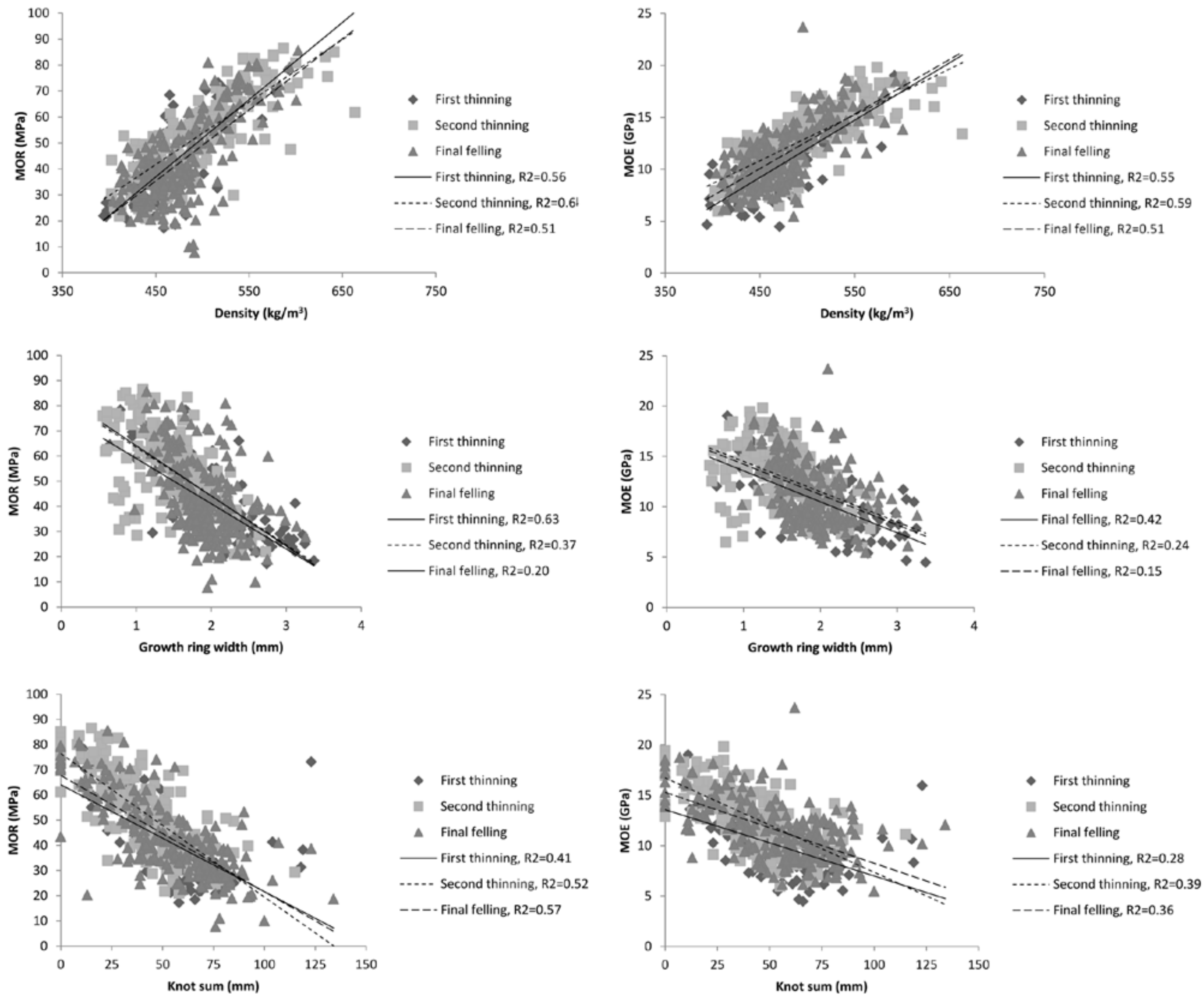


**Figure 5.** Relationships of MOR (MPa) and MOE (GPa) with density (kg/m$^3$), growth ring width (mm), and knot sum (mm), according to stand type

ticity increased along with the increasing wood density (Figure 5). In the boards from the first-thinning stands, the changes in density had a stronger effect on MOE than on the other stand types. Moreover, the knot sum had a negative effect on MOE. The modulus of elasticity was low especially in the boards with the knot sum larger than 50 mm. Based on the regression lines, the knot sum affected MOE more dramatically in the second-thinning boards than in those from the other stand types.

Boards with very low strength were obtained from the first thinnings only (Figure 6). Where the other stand types were concerned, the bending strength of sawn timber was 18 MPa, at minimum. Only 2% of boards remained below 24 MPa in the second thinnings, 11% in the first thinnings, and 6% in the final fellings. In the first thinnings and final fellings, the proportion of boards with the bending strength of 30–39 MPa was the largest, whereas the second-thinning boards most often had the strength of 60 MPa, or even higher. Furthermore, about 17% of the first-thinning and final-felling boards had a very high bending strength of at least 60 MPa.

Based on the characteristic values of strength, density, and modulus of elasticity, the unsorted sawn timber from the first thinnings and final fellings was theoretically graded to C18 and that from the second thinnings to C24 (Table 6). As entire populations, sawn timber from the second thinnings was graded to C24, and that from the other stand types to C18. Sorting by log section raised the

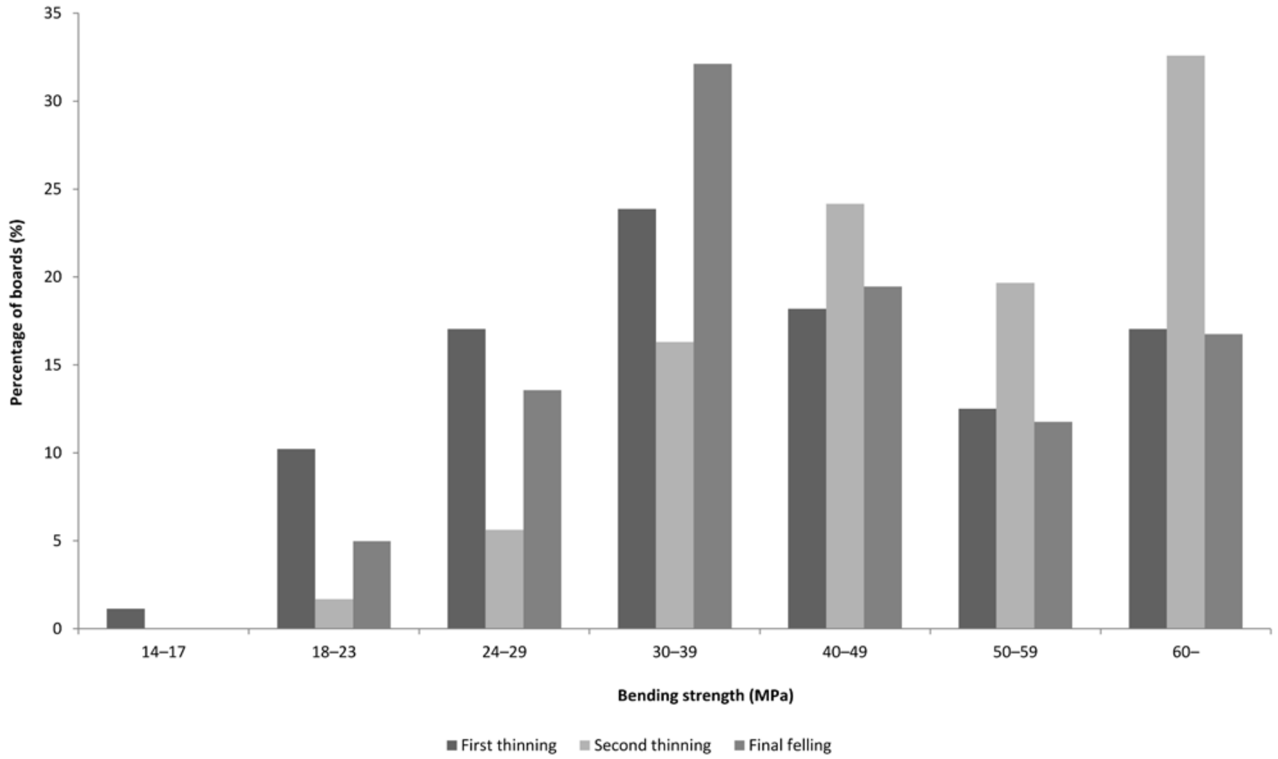


**Figure 6.** Bending strength distribution of the boards, according to the stand type

**Table 6.** Theoretical strength classes of the strata for stand type, log section, and cross-section size (Finnish Standards Association 2010)

| | 1st thinning | 2nd thinning | Final felling | Butt log | Middle log | Top log | 50×50 | 50×75 | 50×100 |
|---|---|---|---|---|---|---|---|---|---|
| 1st thinning | C18 | | | | | | | | |
| 2nd thinning | | C24 | | | | | | | |
| Final felling | | | C18 | | | | | | |
| Butt log | C16 | C35 | C24 | C22 | | | | | |
| Middle log | C18 | C30 | C18 | | C18 | | | | |
| Top log | C16 | C20 | C18 | | | C18 | | | |
| 50×50 | C16 | C16 | C20 | C22 | C14 | C16 | C16 | | |
| 50×75 | C18 | C18 | C20 | C18 | C20 | C18 | | C18 | |
| 50×100 | C20 | C30 | C18 | C22 | C20 | C18 | | | C22 |

strength classes of the butt logs and middle logs of second thinnings into C35 and C30, and the butt logs of final fellings into C24. As a whole, sawn timber from the butt log section corresponded to the strength class C22 and that from the upper stem parts to C18. In general, the 50×50-mm boards fell into the strength class C16, the 50×75-mm boards to C18, and the 50×100-mm boards to C22.

Comparing the theoretical strength classes (C) with the visual strength grades (T) indicated that the visual strength grading somewhat underestimated the properties of boards. In general, approximately 74% of all boards achieved a higher theoretical strength class than indicated by the visual strength grade. As an exception, 42% of the boards graded into T2 were noted to fall into lower theoretical strength classes; especially where the first thinnings were concerned, 64% of the boards had a lower strength class than the C24 indicated by the visual strength grade T2.

## Discussion and conclusions

The study stands represented the typical range of commercial forests in the geographical area in question, the site fertility varying from the *Myrtillus* type on mineral soils to the dwarf-shrub transformed type on drained peatlands. The forest management practice recommendations presume thinnings in commercial forests at certain phases of the rotation period. Especially the first commercial thinnings principally aim at improving the quality of forest for growth, yield, and recovery of desired timber assortments in the future cuttings. The recommended thinning method for Scots pine forests is the thinning for quality, in which the smallest trees, and trees with poor external quality, are removed. Thus, the yield of saw logs is often modest in first thinnings, and, depending on the general quality of the forest, the quality of sawn timber can be markedly lower than in mature forests. In the latter one or two thinnings, sawn timber with higher quality can be expected (Kellomäki et al. 1992, Verkasalo 2002, Stöd et al. 2006). This is due to the fact that, at these stages of rotation period, the growing stock should be a result from tree selection for timber quality. In this study, each felled sample tree was required to contain at least one small-sized log, and thus the quality of sample trees may have been somewhat higher than the quality of trees removed in actual thinnings, especially in the low or average-quality forests, or in forests with smaller average stem size, such as on peatlands. The structure of current study material was uneven, since the number of logs and boards with different dimensions varied markedly between the stand and site types. For instance, only few boards representing the top log were obtained from the first-thinning stands, whereas about half of the final-felling boards were from the top log section. The number of 50×100-mm boards was also markedly higher than those of the smaller board dimensions. Thus, in some strata the characteristic values for defining the theoretical strength classes were calculated for a smaller sample than the minimum sample size stated in the standard.

The method of determining the local modulus of elasticity has been noted to have shortcomings in measuring the deflection, and thus, in producing accurate results (Boström 1999, Holmqvist and Boström 2000). The method is sensitive to the experimental setup; stiffness, especially, is responsive to the duration of loading, and thus, limitations of the long-term deflection must be applied in the design (Desch 1981). Boström (1999) compared the local and global methods, and noted a significant difference between the two (Standards Australia 1992, European Committee for Standardization 1995, American Society for Testing and Materials 2005). Factors such as the length between reference points in the deformation measurement, timber quality, and shear deformations affected the ratio between the results of the local and global method. In the test pieces with small depths, the size of a defect in relation to the distance between the reference points was larger than in the test pieces with large depths. Thus, it was noted that the effect of the critical defect on the modulus of elasticity was more significant for the local method than the global one. The modulus of elasticity is somewhat underestimated in the global method due to the shear deformations, which should be taken into account, when the deformation is measured as the mid-point deflection relative to the supports. For instance, in the study by Hanhijärvi et al. (2005), the average modulus of elasticity for Scots pine was 12.1 GPa, when measured locally, and 11.8 GPa, when measured globally. Piter et al. (2003) noted a difference of 6–7% between the local and global modulus of elasticity of Argentinean *Eucalyptus grandis*, the first-mentioned giving the higher values.

The majority of boards met the quality requirements of the visual strength grade T1, whereas the highest grade T3 was achieved by less than 10% of all boards. The boards mainly represented the centre yield of the logs, owing to which the knot quality of boards was good, especially in the material from the first thinnings. However, also the distortions were the most extensive in the boards from the first thinnings, which may indicate problems in the further processing, especially in drying. The notable occurrence of bow in the first-thinning boards, as well as in the final-felling boards, might be explained by the juvenile-wood effect, as the exceptional shrinkage properties of juvenile wood are known to cause distortions. Here, besides the young wood material from the first thinnings, most of the final-felling boards were sawn from the upper parts of the stem, i.e., from the juvenile-wood area. Since the quality of boards was assessed after an indefinite period of storage outdoors, the board deformations are not comparable with the results for artificially dried sawn timber.

The research on sawn timber has concentrated mainly on the larger logs from final fellings, and there are only a few published studies concerning the properties of timber originating in thinning forests. The pith-enclosed timber from thinnings has been studied by Boren (2001) and Fernández-Golfin et al. (2007). Comparing their results showed that despite the similar level of density, the MOR and MOE of machine-rounded Scots pine were markedly higher than those of laricio pine *(Pinus nigra* Link.*)* (Boren 2001, Fernández-Golfin et al. 2007). Both studies concluded, however, that based on the bending properties, the pith-enclosed timber from thinnings was suitable for structural use. Earlier, the bending properties of round timber have been noted to be 5–15% higher than those of sawn timber, the difference being a result of the negative effect of mechanical tooling on the outer wood fibres of sawn timber (Boren and Barnard 2000). Compared with the round, pith-enclosed materials, the bending strength of sawn timber was markedly higher in this study than that of laricio pine in the study by Fernández-Golfin et al. (2007), and at the same level with Scots pine in the study by Boren (2001). Furthermore, the modulus of elasticity was higher for sawn timber than for pith-enclosed round timber.

Where the final fellings were concerned, sawn timber of this study had somewhat lower bending properties than presented earlier by Lindgren (1996). The difference between the two studies may be explained by the lower wood density of this study, resulting from the different growth conditions of the trees. In comparison with the results by Verkasalo et al. (2007), the properties of sawn timber from the final fellings of this study were at the same level, whereas in the study by Ranta-Maunus (2007), the bending properties of Swedish Scots pine sawn timber were lower than those reported in this study.

The variation of the bending properties was the largest in the first thinnings and the smallest in the second thinnings, indicating more homogeneity in the recovery after selection through cuttings. The variation also decreased from the butt logs to the top logs, indicating the effect of less transverse variation in the pieces of sawn timber that were obtainable. Compared with the data of larger pine logs (Hanhijärvi et al. 2005, Hanhijärvi and Ranta-Maunus 2008), the variation of MOE was notable for the thinning material. The unpredictability of critical properties decreases the competitiveness of timber in comparison to other, more homogenous materials. Hudson (1967), for example, noted the considerable differences between the individual pieces of European redwood sawn timber within samples to mask the variations of the strength properties between the regions. Johansson and Kliger (2000) named the lack of consistent, predictable, reproducible, and uniform properties as the main disadvantage of timber as engineering material.

In this study, the first thinnings provided sawn timber with the lowest MOR and MOE, whereas the material from the second thinnings provided the highest. The properties of sawn timber from final fellings lay between the other two stand types. However, when comparing the stand types, their different growth-affecting characteristics should be taken into account. The final-felling stands were located solely in the most fertile site type, while the second-thinning stands were mostly poor in nutrients. This was indicated also by the growth rate of the trees; the average growth ring width of 1.7 mm, at the stump height, was measured for the final-felling trees, 1.2 mm for the second-thinning trees, and 1.8 mm for the first-thinning trees. The average age of the felled sample trees was 44 years in the first-thinning stands, 85 years in the second thinnings, and 82 years in the final-felling stands. Thus, the order of the second-thinning trees and the final-felling trees for the bending properties could be explained by the relatively high age and slow growth of the second-thinning trees, or reversely, by more rapid growth of final-felling trees caused by the favourable growth conditions. In the second thinnings, especially the sample trees from the *Calluna* type and the dwarf-shrub transformed type stands increased the average tree age, and represented the slowest growth. Earlier, in a case study by Stöd and Verkasalo (2005), very high bending properties were observed for Scots pine sawn timber from commercial second-thinning operations, the means of MOR, MOE, and density being 55.1 MPa, 13.6 GPa, and 525 kg/m$^3$, respectively.

For the other pine species, Clark et al. (1996), for example, noticed a clearly better strength grade distribution of loblolly pine (*Pinus taeda* L.) sawn timber at the rotation age of 40 years compared to less than 30 years. McAlister et al. (1997) noted the modulus of elasticity of loblolly pine timber to be significantly higher at the rotation age of 40 years than at 28 or 22 years. Duchesne (2006) found a systematically better MOR and MOE of jack pine (*Pinus banksiana* Lamb.) sawn timber at the rotation age of more than 70 years compared to 50 years, and a decreasing trend in the strength, in particular, by growing dbh class of trees. In the studies by McAlister et al. (1997) and Duchesne (2006), the bending properties of jack pine and loblolly pine were approximately at the same level as in this study. The comparability of the bending properties of Scots pine and loblolly pine has been reported in the literature survey by Grekin (2006).

The highest values of MOR and MOE of this study were measured from the butt log section, and the lowest values close to the tree top. In the butt log section, the differences between the stand and site types were moderate. At the low and moderate levels of density, MOR and MOE were relatively even in the different log sections, and an increment in density affected strength more the lower the position of the log section. The vertical within-tree variations of wood properties are well-known; in the tree species having the increasing density from pith to bark, density decreases markedly from butt to top, and along with it several other wood properties change following the same trend. In maritime pine (*Pinus pinaster* Ait.), for instance, a decrease greater than 20% in MOR and MOE has been noted between the stem height levels of 35% and 65% (Machado and Cruz 2005). In the studies by Duchesne (2006) and Zhang et al. (2006), the MOR, MOE, and density of jack pine decreased from butt to top. Johansson and Kliger (2000) noted concerning to Norway spruce timber that battens sawn from the first or second logs had significantly higher bending strength and modulus of elasticity than battens from the upper parts of tree. Also, according to Haartveit and Flæte (2002), the increased vertical position in the tree had a negative effect on the MOR and MOR of Norway spruce timber.

Density is usually the most important factor affecting the mechanical wood properties, and their variation follows the development of density within a stem. Also in this study, the wood density had a strong positive effect on both MOR and MOE. Very high basic density (over 500 kg/m$^3$) was noted in *Calluna* type, in contrast with the more typical basic density levels in *Vaccinium* and *Vaccinium vitis-idaea* types. Where timber from first thinnings was concerned, density was at the same level with those of earlier studies; in the study by Hakkila et al. (1995), for instance, the basic density of young Scots pine wood was approximately 395 kg/m$^3$ in southern Finland. In Sweden, the basic density of pine saw logs from thinnings was 425 kg/m$^3$ (Björklund and Walfridsson 1993). The density decreased within the trees of this study from butt to top, the difference between the lowermost and the uppermost stem parts being approximately 57 kg/m$^3$. Repola (2006) noted an even larger difference, approximately 100 kg/m$^3$, between the butt and the top of Scots pine trees, and Björklund and Walfridsson (1993) found a difference of 90 kg/m$^3$ between the stump and the merchantable top of thinning trees.

A good growth of trees normally results in a large early wood proportion within the year rings (e.g. Kellomäki et al. 1992, Kärkkäinen 2007). As early wood is, due to the lower density, weaker than late wood, increment in the early wood proportion decreases MOR and MOE. The effect of ring width is not, however, caused solely by density; the weaker zone formed by early wood, and enabling cracks, as well as the increasing microfibril angle in the middle layer $S_2$, have been mentioned as the possible reasons for the phenomenon that even with constant density, bending strength is higher the narrower are the year rings (Kärkkäinen 2007). Additionally, in the fast-grown trees branches grow thick, which results in wood material with large knots, and, consequently, in lower strength (Lämsä et al. 1990). The growth conditions, which promote tree growth most, are the nutrient-rich site, and the wide spacing of trees (Kellomäki et al. 1992). The growth rate of the trees was noted to affect the strength properties in this study. In 9% of the sample trees the annual growth exceeded 2.5 mm, which in the Nordic visual strength grading rules is considered as the upper limit for the slow growth favourable for the quality of sawn timber (Finnish Standards Association 2010).

The average strength of the 50×50-mm boards was higher than that of the middle-sized, 50×75-mm boards, and almost as high as of the largest 50×100-mm boards. Where the modulus of elasticity was concerned, it was noted to increase along with the board dimensions being lowest in the 50×50-mm boards and highest in the 50×100-mm boards. Density, in turn, was notably lower in the 50×50-mm boards than in the 50×100-mm boards. The smallest boards were sawn mainly from the top log section, thus not explaining the nearly equal average strength of the boards. Instead, the small size, which decreases the probability of the occurrence of knots and other defects, could, to some extent, explain the good strength level of the 50×50-mm boards. The effect of the object size on the probability of a weak point was presented by Bohannan in 1966, and it is based on a statistical strength theory originally suggested by Weibull in 1939. In bending, the length effect has been noted to be more significant than the depth effect, due to the lengthwise variation of stresses in a piece of timber (Isaksson 2003). Due to the size requirements set for the bending test pieces, in addition to the smaller cross-sectional area, the 50×50-mm boards were also shorter than the 50×75-mm or the 50×100-mm boards.

A piece of timber consists of weak zones containing defects, such as knots, groups of knots, or deviate grain angle, and the clear wood connecting them (Källsner et al. 1997, Ditlevsen and Källsner 1998, Isaksson 2003). Basically, the larger the size and the more frequent the defects in a piece of sawn timber are, the smaller the relative effect of the clear wood properties on its properties (Bodig and Jayne 1982; Madsen 1992; Hanhijärvi et al. 2005). The knots affect the mechanical properties through the tension perpendicular to grain in their vicinity, as well as the deviate angle of cells in the knots and the grain distortions near to them (Desch 1981, Bodig and Jayne 1982, Hoffmeyer 1995, Forest Products Laboratory 2010, Kärkkäinen 2007). The effect of knots, however, varies from one mechanical property to another. Knots decrease most strongly the longitudinal tensile strength, compression strength parallel to the grain, and bending strength; in general, knots have been noted to have a greater effect on the strength properties than on the modulus of elasticity (Desch 1981, Bodig and Jayne 1982, Forest Products Laboratory 2010). However, the individual large knots had no effect on the bending properties in this study, but the knot sum was noted to affect the modulus of elasticity.

In every tenth board, the section of board with the largest knot sum was noted to equal the location of visually estimated weakest point of the board.

The theoretic strength-class distribution of samples indicated a strong focus on the strength classes of C30, or higher, for the sawn timber from the second thinnings, but, in contrast, on the strength classes of C24, or lower, for the sawn timber from the first thinnings. Samples reaching the highest strength classes were found only in the second thinnings, and the weakest samples only in the first thinnings. Comparing the results with those from the visual strength grading showed that especially in the highest strength classes, the visual evaluation somewhat underestimated the quality and properties of sawn timber. As an exception, the majority of first-thinning boards, which had been graded visually to T2, had a lower strength class than the C24. This may be due to the fact that in 86% of all the boards, the modulus of elasticity was noted to be the critical factor affecting the potential strength class; thus, despite the good strength and density values of the boards, the low level of MOE decreased their estimated strength classes. As stated earlier, the MOE of wood is determined by the clear wood properties rather than by the local weak points (Hanhijärvi et al. 2005, Hanhijärvi and Ranta-Maunus 2008). In the first thinnings, where the difference between the visual strength grading and the strength classes given by the results from destructive tests, the visual quality of boards was good, but the other factors, such as wood density, were lower than on the other stand types.

This study indicated that the quality of young Scots pine trees may be favourable for producing sawn timber with good bending properties. The assessment based on the visual grading rules of sawn timber showed very high quality potential of boards originating in thinning forests. The visual evaluation and the standardised tests indicated that Scots pine sawn timber with comparable or, in some cases, even better bending properties for structural products may be obtained from second commercial thinnings than from the current final fellings. The bending properties of sawn timber from the first thinnings are generally lower, even though still mainly acceptable for structural uses. The potential for structural timber is the best in sawn timber from the butt logs, and, moderate in sawn timber from the middle logs. Further research is needed to confirm the effects of site fertility, and silvicultural and cutting regimes on the mechanical properties of timber from thinnings, as well as on its shape and dimensional stability, moisture distribution, and applicability for machining and mechanical connecting. The specific characteristics and true effects of juvenile wood and reaction wood in thinning trees should also be precise. It appears that the negative effects of juvenile wood may have been overestimated for northerly-grown Scots pine, even for younger cultivated trees. Instead, the negative effects of reaction wood in young trees with poorer stem straightness may have been somewhat underestimated.

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## References

American Society for Testing and Materials. 2005. ASTM D4761, Standard test methods for mechanical properties of lumber and wood-based structural material. 10 pp.

**Björklund, L. and Walfridsson, E.** 1993. Tallvedens egenskaper i Sverige - Torr-rådensitet, kärnvedhalt, fuktighet och barkhalt. [Properties of Scots pine wood in Sweden: basic density, heartwood, moisture and bark content.] Sveriges Lantbruksuniversitet, Institutionen för virkeslära, Rapport nr. 234. 67 pp. (in Swedish)

**Bodig, J. and Jayne, B. A.** 1982. Mechanics of wood and wood composites. Van Nostrand Reinhold Company, New York, 712 pp.

**Bohannan, B.** 1966. Effect of size on bending strength of wood members. U. S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WIS, Research Paper FPL 56, 30 pp.

**Boren, H. and Barnard, G.** 2000. Analysis of the strength and stiffness properties for small round Scots pine timber tested in bending and compression parallel to grain. *Paper and Timber* 82(1): 48–56.

**Boren, H.** 2001. Factors affecting the knottiness, twisting and mechanical properties of pith enclosed round and sawn timber of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) from thinnings in Southern Finland. Finnish Forest Research Institute, Research Papers 807, 164 pp.

**Boström, L.** 1994. Machine strength grading, comparison of four different systems. Swedish National Testing and Research Institute, Building Technology, SP Report 49, 57 pp.

**Boström, L.** 1999. Determination of the modulus of elasticity in bending of structural timber: comparison of two methods. *Holz als Roh- und Werkstoff* 57: 145–149.

**Cajander, A.K.** 1949. Forest types and their significance. *Acta Forestalia Fennica* 56(5): 1–71.

**Clark, A. III, McAlister, R. H., Saucier, J. R. and Reitter, K.** 1996. Effect of rotation age on lumber grade, yield, and strength of unthinned loblolly pine. *Forest Products Journal* 46(1): 63–68.

**Desch, H. E., rev. by Dinwoodie, J. M.** 1981. Timber: its structure, properties and utilisation, 6th edn. MacMillan Education Ltd, London, 410 p.

**Ditlevsen, O. and Källsner, B.** 1998. System effects influencing the bending strength of timber beams. In: A. S. Nowak (Ed.), Proceedings of the IFIP 8th WG 7.5 Working Conference on Reliability and Optimization of Structural Systems, Krakow, Poland, May 11–13. University of Michigan, Ann Arbor: 129–136.

**Duchesne, I.** 2006. Effect of rotation age on lumber grade yield, bending strength and stiffness in Jack pine (*Pinus banksiana* Lamb.) natural stands. *Wood and Fiber Science* 38(1): 84–95.

European Committee for Standardization CEN. 1995. EN 408. Timber structures, Structural timber and glued laminated timber, Determination of some physical and mechanical properties, 19 pp.

**Fernández-Golfín, J. I., Díez-Barra, M. R., Hermoso, E. and Mier, R.** 2007. Mechanical characterization of visually classified, small-diameter laricio pine round timber. *Spanish Journal of Agricultural Research* 2007 5(3): 304-311.

Finnish Forest Research Institute. 2013. Finnish Statistical Yearbook of Forestry. 450 pp.

Finnish Standards Association SFS. 2003. SFS-EN 408. Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties, 31 pp.

Finnish Standards Association SFS. 2010. SFS 5878 INSTA 142. Sahatavaran visuaalisen lujuuslajittelun pohjoismaiset säännöt. [Nordic visual strength grading rules for timber], 16 pp. (in Finnish).

Finnish Standards Association SFS. 2010. Standard SFS-EN 338. Structural timber. Strength classes, 11 pp.

Finnish Standards Association SFS. 2010. Standard SFS-EN 384. Structural timber. Determination of characteristic values of mechanical properties and density, 20 pp.

**Flæte, P. O., Kucera, B. and Haartveit, E.Y.** 2001. Strength and related properties of Norway spruce timber in structural sizes. Comparison of spruce grown in mixtures with birch and in monocultures. In: Bergstedt, A., Kucera, B., Nylinder, M., Saranpää., P., Ståhl., E. (Eds.). Wood quality of Norway spruce grown in mixture with birch and in monoculture. Finnish Forest Research Institute, Research Papers 822: 41–49.

Forest Products Laboratory. 2010. Wood handbook – Wood as an Engineering Material. General Technical Report FPL-GTR-190. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI., 508 pp.

**Glos, P.** 1995. Strength grading. STEP lecture A6. In: Blass, H. J., Aune, P., Choo, P., S., Görlarcher, R., Griffits, G., R., Hilson, B. O., Racher, P. and Steck, G. (Eds.), Timber engineering. STEP 1. Basis of design, material properties, structural components and joints. Centrum Hout, The Netherlands p. A6/1–A6/8.

**Grekin, M.** 2006. Nordic Scots pine vs. selected competing species and non-wood substitute materials in mechanical wood products. Literature survey. Working Papers of the Finnish Forest Research Institute 36, 66 pp..

**Haartveit, E. Y. and Flæte, P. O.** 2002. Mechanical properties of Norway spruce lumber from monocultures and mixed stands – modelling bending stiffness and strength using stand and tree characteristics. In: Nepveu, G. (Ed.). Iufro WP S5.01.04, Proceedings from the Fourth workshop “Connection between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software: 346–355.

**Hakkila, P., Kalaja, H. and Saranpää, P.** 1995. Etelä-Suomen ensiharvennus männiköt kuitu- ja energiapuunlähteenä [Southern Finland thinning pine forests as a source of fiber and energy.]. Finnish Forest Research Institute, Research Papers 582, 99 pp. (in Finnish).

**Hanhijärvi, A., Ranta-Maunus, A. and Turk, G.** 2005. Potential of strength grading of timber with combined measurement techniques. Report of the Combigrade-project: phase 1. VTT Publications 568, 81 pp.

**Hanhijärvi, A. and Ranta-Maunus, A.** 2008. Development of strength grading of timber using combined measurement techniques. Report of the Combigrade-project: phase 2. VTT Publications 686, 55 pp.

**Hoffmeyer, P.** 1995. Wood as a building material. STEP lecture A4. In: Blass, H. J., Aune, P., Choo, P., S., Görlarcher, R., Griffits, G., R., Hilson, B. O., Racher, P. and Steck, G. (Eds.). Timber Engineering. STEP 1. Basis of design, material properties, structural components and joints. Centrum Hout, The Netherlands, p. A4/1–A4/20.

**Holmqvist, C. and Boström, L.** 2000. Determination of the modulus of elasticity in bending of structural timber – comparison of two methods. In: Proceedings of the World Conference on Timber Engineering. Whistler, British Columbia, 8 pp.

**Hudson, W. M.** 1967. The strength properties of European redwood and whitewood. Ministry of Technology, Forest Products Research, Special Report No 24, 25 pp.

IBM SPSS Statistics. http://www-01.ibm.com/software/analytics/spss/products/statistics/

**Isaksson, T.** 2003. Structural timber: variability and statistical modelling. In: Thelandersson, S. and Larsen, H. J. (Eds.). Timber engineering. John Wiley & Sons, London, p. 45–66.

**Johansson, C. J.** 2003. Grading of Timber with Respect to Mechanical Properties. In: Thelandersson, S. and Larsen, H. J. (Eds.), Timber engineering. John Wiley & Sons, London, P. 23–43.

**Johansson, M. and Kliger, R.** 2000. Variability in strength and stiffness of structural Norway spruce timber: influence of raw material parameters. In: Barrett, J. D (Ed.). Proceedings of the World Conference on Timber Engineering. Whistler, British Columbia, Canada: 9.

**Kellomäki, S., Lämsä, P., Oker-Blom, P. and Uusvaara, O.** 1992. Männyn laatukasvatus. [Management of Scots pine for high quality timber.] *Silva Carelica* 23. 133 pp. (in Finnish with English abstract).

**Källsner, B., Ditlevsen, O. and Salmela, K.** 1997. Experimental verification of a weak zone model for timber in bending. In: Hoffmeyer, P. (Ed.). IUFRO S5.02 Timber engineering, Proceedings of the 1997 Conference. Technical University of Denmark, Department of Structural Engineering and Materials: 389–404.

**Kärkkäinen, M.** 2007. Puun rakenne ja ominaisuudet. [The structure and properties of wood]. Metsäkustannus, Hämeenlinna, 468 pp. (in Finnish).

**Lindgren, C.** 1996. Sahatavaran visuaalinen ja koneellinen lujuuslajittelu. [Visual and machine strength grading of sawn timber.] Master’s thesis. Helsinki University of Technology, Department of Forest Products Technology, 75 pp. (in Finnish).

**Lämsä, P., Kellomäki, S. and Väisänen, H.** 1990. Nuorten mäntyjen oksikkuuden riippuvuus puuston rakenteesta ja kasvupaikan viljavuudesta. [Branchiness of young Scots pine as related to stand structure and site fertility]. *Folia Forestalia* 746: 1–22 (in Finnish).

**Machado, J. S. and Cruz, H. P.** 2005. Within stem variation of Maritime pine timber mechanical properties. *Holz als Roh- und Werkstoff* 63: 154–159.

**Madsen, B.** 1992. Structural behaviour of timber. DW Friesen, Altona, Manitoba, Canada, 405 pp.

**McAlister, R. H., Clark, A. III and Saucier, J. R.** 1997. The effect of age at harvest on bending and tensile properties of loblolly pine from the Coastal Plain. *Forest Products Journal* 47(5): 85–88.

**Paavilainen, E. and Päivänen, J.** 1995. Peatland forestry: Ecology and principles. Ecological studies 111. Springer-Verlag, Berlin, 248 pp.

**Packalen, T., Salminen, O., Hirvelä, H., Härkönen, K., Lempinen, R. and Anola-Pukkila, A.** 2015. Aines- ja energiapuun hakkuumahdollisuudet [Cutting potential of industrial roundwood and energywood] Natural Resources Institute Finland

(Luke). http://www.luke.fi/wp-content/uploads/Aines-ja-energiapuun-hakkuumahdollisuudet.pdf, (in Finnish).

**Piter, J. C., Zerbino, R. L. and Blaß, H. J.** 2003. Relationship between global and local modulus of elasticity in beams of Argentinean *Eucalyptus grandis*. *Maderas, Ciencia y tecnología* 5(2): 107–116.

**Priedkalns, G., Pušinskis, V., Dolacis, J. and Hrols, J.** 2006. Strength studies of sawn timber produced of Norway spruce (*Picea abies* L. Karsten.) grown in Latvia. In: Kurjatko, S., Kúdela, J. and Lagana, R. (Eds.). Proceedings of the 5th IUFRO symposium Wood Structure and Properties '06 held on September 3–6, 2006 in Sliac–Sielnica, Slovakia. Arbora Publishers, Zvolen: 365–367.

**Ranta-Maunus, A.** 2007. Strength of Finnish grown timber. VTT Publications 668, 60 pp..

**Repola, J.** 2006. Models for vertical wood density of Scots pine, Norway spruce and birch stems, and their application to determine average wood density. *Silva Fennica* 40(4): 673–685.

**Salminen, O.** 2014. Suomen metsien kehitys ja hakkuumahdollisuudet [Development and cutting potential of Finnish forests] ForestEnergy 2020 Seminar, Jyväskylä, Finland. Finnish Forest Research Institute. http://www.forestenergy2020.org/openfile/271 (in Finnish)

Standards Australia. 1992. AS/NZS 4063. Timber, stress-graded: In-grade strength and stiffness evaluation, 16 pp.

**Stöd, R. and Verkasalo, E.** 2005. Strength and stiffness of Scots pine sawn timber from commercial thinnings. Finnish Forest Research Institute, Joensuu Research Centre *(Manuscript),* 21 pp.

**Stöd, R., Kilpeläinen, H. and Wall, T.** 2006. Yield and technical quality of Scots pine saw timber from thinnings on drained peatlands and mineral soils in Finland. *Baltic Forestry* 12(2): 170-183.

**Verkasalo, E.** 2002. Development of procurement and sawmilling of Scots pine from thinnings. In: Paavilainen, L. (Ed.). Final report, Finnish Forest Cluster Research Programme WOOD WISDOM (1998–2001), p.. 333–340.

**Weibull, W.** 1939. A statistical theory of the strength of materials. *Ingeniörs Vetenskaps Akademien-Handlingar* 151: 1–45.

**Zhang, S. Y., Chauret, G., Swift, E. and Duchesne, I.** 2006. Effects of precommercial thinning on tree growth and lumber quality in a jack pine stand in New Brunswick, Canada. *Canadian Journal of Forest Research* 36(4): 945–952.

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