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ORIGINAL ARTICLE

Using non-destructive testing to assess modulus of elasticity of *Pinus sylvestris* trees

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Abstract

This study assessed variation in modulus of elasticity of trees and logs of Scots pine (*Pinus sylvestris*) trees. The study used 192 sample trees (*c.* 90–150 years) selected from 24 clear-felling forests in central and southern Sweden. Modulus of elasticity (MOE) assessed with transit-time technology on standing tree stems at 0.5–2.0m on the southern and northern side of each tree varied from 8.6 to 17.6 GPa. No systematic MOE difference was found between the southern and northern side of tree stems. The sometimes large MOE variations seen in some individual trees are probably a result of wood variation and wood defects. MOE assessed with resonance-based technology varied between 7.4 and 14.1 GPa for logs cut at similar height (<6.0 m). Models of MOE variation were derived from factors related to growth conditions at stand and tree level, with an $R^2{}_{adj}$ of *c.* 0.46–0.62. The models indicate that growth and tree attributes associated with and/or creating less stem taper would yield trees with higher MOE.

Keywords: *Acoustics, growth conditions, modulus of elasticity, Pinus sylvestris, wood quality.*

Introduction

Old-growth forests are gradually being replaced by forests established and managed to reach commercial tree size at an earlier age. This will change the material properties of conifer wood as fast-grown trees, in comparison to more slowly grown trees, will contain a larger proportion of juvenile wood, knots and compression wood (Thörnqvist, 1993; Kennedy, 1995; Moberg, 2001; Lindström, 2002; Warensjö & Rune, 2004). Using more intense silvicultural regimes can be seen as a direct result of economic demands. Here, the goal will be to produce fast-grown trees that reach commercial tree age at low age. Logs cut from such trees (fast grown/low age) would bring higher production costs and lower revenue of solid wood products in the sawmill industry as the proportion of sawn lumber with unacceptable drying distortion, low modulus of elasticity and large knots would increase (Kennedy, 1995).

However, the ongoing trend towards a general decline in average wood quality will be blurred by the fact that there still will be plenty of trees of average to good quality in future forests. In other words, there will be increased emphasis on methods to improve log sorting and optimized cross-cutting of tree stems to achieve optimal industrial use of a more mixed quality forest resource (Roos et al., 2001). This has already been seen in the research initiatives concerned with grading of logs and trees according to their material properties (Perstorper, 1994; Oja et al., 2001, 2004; Tsehaye et al., 2001; Albert et al., 2002; Beall, 2002; Huang et al., 2003; Edlund et al., 2006; Grekin, 2007), where derived technologies and methods are aimed at directing stems and logs to the best industrial end-use.

One important wood property is the modulus of elasticity (MOE), often referred to as material stiffness. High MOE means that a material can carry a high load without strain or deformation. MOE is also correlated with the strength of wood: modulus

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of rupture (Dinwoodie, 2000). Because MOE of sawn lumber can be tested non-destructively by machine stress grading (Anon., 2006*a*) and by acoustics (Anon., 2006*b*) it is used as a grading criterion for construction lumber (Anon., 1995, 2000). As there is also clear agreement between structural lumber grade and the assessed MOE of sawlogs (Ross et al., 1997; Edlund et al., 2006), measurements of log MOE could possibly be used to presort logs into timber property classes.

Acoustic analysis of wood variation has been performed with methods based on transit time, resonance frequency, ultrasound and wavelength spectra analysis (Bucur, 1995; Ouis, 1999; Lindström et al., 2002, 2005; Solodov et al., 2004; Bucur & Bohnke, 2005; Chauhan et al., 2005; Dyk & Rice, 2005; Gozdecki & Smardzewski, 2005; Chauhan & Walker, 2006). These studies have shown that acoustics can be used to describe wood features that affect the visual appearance and drying distortion of solid wood products, e.g. knot structure, wood rot, fibre dimension and microfibril angle. Accordingly, acoustics has been used as a practical, low-cost method to assess the wood quality of standing trees, cut logs and sawn lumber for a range of softwood species. Here, the focus has been either to use MOE as a genetic selection trait or to model wood quality variation in response to growth conditions (Marchal & Jacques, 1999; Wang et al., 2001; Huang et al., 2003; Lindström et al., 2004; Xu & Walker, 2004; Grabianowski et al., 2006; Wang & Simpson, 2006; Watt et al., 2006; Cherry et al., 2008). Similar models could possibly be used in timber procurement and/or be used to link a given wood resource with industrial requirements of solid wood products, e.g. in consideration of structural or joinery product requirements.

The current study uses 24 clear-felling forests to explore the approximate range of MOE found in Scots pine timber trees selected from two regions of central Sweden. The objectives of the study were (1) to use transit-time technology and resonance-based technology to assess typical MOE variation in Scots pine tree stems at the time of clear-felling; and (2) to model MOE variation in tree stems based on factors related to tree growth.

Materials and methods

This study is part of a collaborative research project between the Finnish Forest Research Institute (METLA) and the Swedish University of Agricultural Sciences (SLU). The aim of this project was to explore and model wood property variation in mature Scots pine timber trees throughout Finland and Sweden. However, only trees on Swedish sites (Figure 1) were available for transit-time and resonance frequency assessment. The Swedish forest sites were selected from inventory records of forests belonging to the forest company Sveaskog. This gave access to suitable clear-felling forests, approximately 90–150 years old, representing forests with low, average and high site index in the Dalarna region and in the Småland region (Figure 1).

The study was based on 192 Scots pine trees selected from 24 sites representing clear-felling forests around 90–150 years old, with yearly growth rates varying between approximately 3 and 12 m^3. Although the selection of stands and trees in this study was designed to cover as much variation in growth conditions as possible, it is rather limited material. Therefore, it is assumed that the natural MOE variation of Scots pine trees would be larger than the variation seen in the descriptive data (Table I) of the current study.

For each selected forest a comprehensive set of standardized stand and tree data was either gathered from inventory data or recorded at the time of tree sampling. All selected sites had to meet the following selection criteria: (1) selected sites should represent the variation in site index for each region (low–medium–high site indices) with a vegetation cover

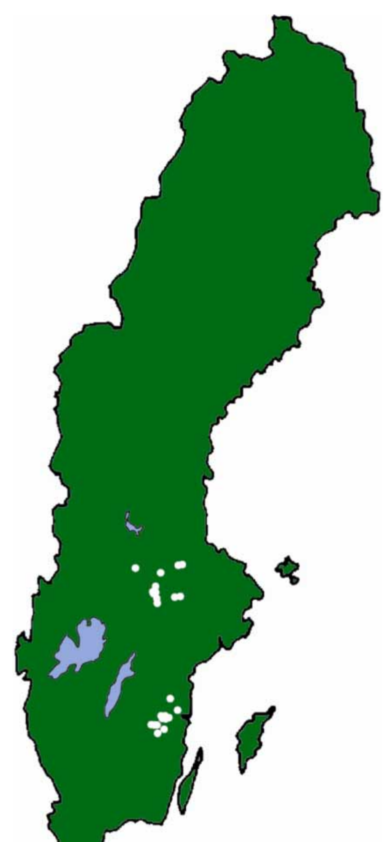

Figure 1. Geographical distribution of the 24 forest sites.

Table I. Minimum, maximum and mean values of modulus of elasticity (MOE) assessed on standing trees and logs.

MOE assessment	No. of observations (n)	Min. MOE (GPa)	Max. MOE (GPa)	Mean MOE (GPa)
MOE calculated according to eq. (2)	189	8.6	17.5	13.9
MOE calculated according to eq. (3)	953	4.7	14.1	9.8

representing *Calluna* type (CT)–*Vaccinium* type (VT) to more fertile *Myrtillus* type (MT); (2) selected tree stands should grow on mineral soil; (3) selected tree stands should be dominated by pine trees (more than 50% of the total stem basal area per hectare); (4) selected tree stands should be planned for commercial clear-felling within 2 years; (5) selected tree stands should have had no extreme silvicultural treatment; and (6) selected tree stands should be close to a road for easy access and transport.

Tree selection

A circular sample plot (*c.* 500–1000 m^2) was laid out in each selected forest stand. The geographical location (longitude, latitude, height above sea level) and the area of each sample plot were registered. The area and the location of each sample plot were decided by stand regularity and stand density in order to contain at least 16 trees, of which at least eight should be pine trees with a diameter at breast height (dbh) larger than 14 cm. Tree species was recorded and diameter was measured with a caliper for all trees on the sample plot exceeding 7 cm at breast height. To select sample trees that represented the tree diameter distribution of each plot, all pine trees on a plot with a dbh larger than 14 cm were callipered and sorted in ascending diameter, then marked with spray paint with a sequential diameter rank with the numbers $\{1, 2, 3, \ldots, n\}$. The n pine trees with dbh larger than 14 cm on each plot was divided by 8:

$$\frac{n}{8} = i \qquad (1)$$

The trees on the plot that had a sequential diameter number closest to the whole numbers $\{i, 2i, 3i, \ldots, 8i\}$ in eq. (1) were selected as sample trees and marked with the diameter rank numbers $\{1, 2, 3, \ldots, 8\}$ to indicate tree class, where 1 = smallest sample tree and 8 = largest sample tree within each sample plot. Directly after felling, each of the eight sample trees was marked with spray paint for the northern exposure along the entire stem. This provided the possibility to evaluate any systematic difference in wood properties between the southern and northern stem side of cut logs, stem bolts and discs that were later cut from each sample tree (see Figure 4).

Transit-time measurements on standing trees

Using the transit-time tool FAKOPP™ (Lindström et al., 2002; Anon., 2006*c*; Grabianowski et al., 2006), three piezoceramic steel probes were attached to the northern stem side of each selected sample tree at approximately 0.1, 0.5 and at 2.0 m from stump height (Figure 2a). The distance between probes was then recorded to the nearest 0.5 cm using a graded steel measurement tape. Impulse waves were launched by a hammer tap to the lowest steel probe and 10 consecutive readings of transit time (ms) were read on a digital display linked to the transit-time readings fed from the location of the second and third steel probes. The same

Table II. Correlation between transit-time measurements on standing trees and the resonance frequency measurements on logs cut from increasing stem heights.

Total no. of observations at each log position varies from the total number of sampled trees (n = 192) because:	Log no. from stump height (1–7) approx. stem height	Coefficient of determination (R^2)	No. of observations (n)
Three high-diameter/short 1st logs were not measured with resonance frequency	1st log (*c.* 0–2 m)	0.72	186
	2nd log (*c.* 2–6 m)	0.44	189
Three stems could only be measured with transit time on one side of the stem	3rd log (*c.* 6–10 m)	0.30	187
	4th log (*c.* 10–14 m)	0.19	177
There was a diminishing number of logs available at increasing stem height	5th log (*c.* 14–18 m)	0.21	127
	6th log (*c.* 18–22 m)	0.09	64
	7th log (*c.* 22–26 m)	0.22	7

(a)

(b)

Figure 2. (a) Transit-time measurements on standing sample trees at 0.5–2.0 m on the northern and southern side of stems using the Fakopp™ tool. (b) Resonance frequency measurements of logs cut from the sample trees using a Rion-SA77 signal analyser.

measurement procedure was undertaken on the southern side of each stem.

The transit-time and distance measurements were used to calculate the average transit-time velocity between the second and third probes for the northern and southern side of each tree. The intention was here to determine whether there are any systematic differences in MOE that can be attributed to the northern and southern exposure of a tree. Moreover, the readings intended to establish whether there could be major differences in MOE on the opposite sides of an individual tree. The MOE of the northern and southern side of the trees was calculated as:

$$\mathrm{MOE} = \rho V^2 \tag{2}$$

where V is the measured transit-time velocity. The green density of the wood (ρ) was not measured in the field; instead, it was assumed to be 800 kg m^{-3} as freshly felled Scots pine varies between about 700 and 1000 kg m^{-3} (Nylinder, 1961). The assumption of ρ being 800 kg m^{-3} may have led to an underestimation or overestimation of the MOE of $\pm$10–25%. For three of the trees consistent impulse velocity readings could not be achieved, as they were standing on shallow, stony soil and severe windsway of the trees triggered impulses that were received by the transit-time probes. The correlation between the MOE measured on the northern and southern side of 189 stems can be seen in Figure 3. The slope of the curve in Figure 3 indicates that there is no difference in MOE between the northern and southern sides of a tree stem. Instead, the substantial MOE scatter within trees (Figure 3) was caused by differences in impulse wave velocity that reflect differences in wood structure, knot size and defects in diametrically opposed stem sectors.

Tree and knot characteristics

The eight selected sample trees in each tree stand were felled and marked with a permanent marker on

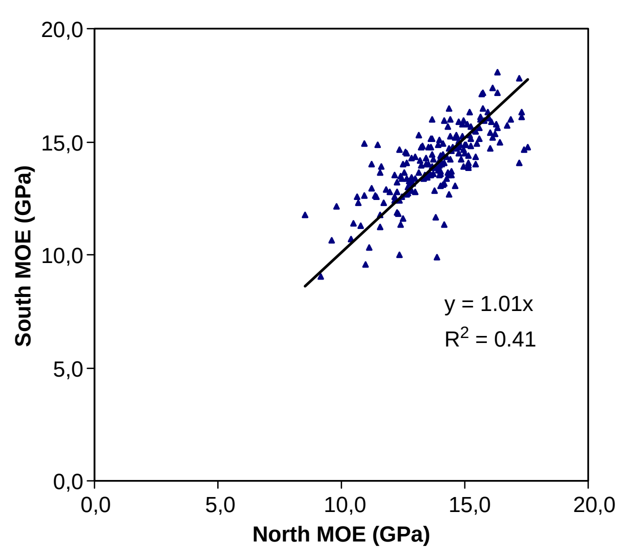

Figure 3. Transit-time measurements for the southern and northern stem side of 189 sample trees. As the regression slope for the modulus of elasticity (MOE) data is close to 1 (1.01*x*) it is assumed that no systematic differences exist in MOE between the southern and northern side of a stem.

the stem end-surface with tree size number 1–8 and the plot number. These trees were then felled, delimbed and marked for bucking without cross-cutting. A continuous coloured line was marked with spray paint to denote the northern exposure of each stem before any further measurement. Stems were then cross-calipered to obtain stem diameter measurements at successive stem heights up each stem: 0, 1.3, 2, 4, 6 m, and so on to the top of the tree. A stem disc was cut at stump height for growth ring determination of tree age in the laboratory. External height limits (dm) for knottiness (no visible knots), tree height, crown height and the diameters of the biggest sound and dry knots were also recorded. External defects were noted as the height where the defect starts, the height where the defect ends and defect type. Stem discs, stem bolts and logs were cut from stems according to the sampling scheme that is further described below and in Figure 4. All heights were recorded starting at stump height. The assessed MOE for trees (eq. 2) and logs (eq. 3) can be seen in Table I.

Measurements of other wood properties and growth ring structure

This study used a preset sampling scheme at successive stem heights for later measurements of heartwood content and growth ring structure on stem discs and measurements of wood properties on stem bolts. That is, 20 cm discs and 70 cm bolts were cross-cut from predetermined stem heights using two alternative cross-cutting patterns (A and B trees), yielding log lengths of approx. 1.8–4.0 m (Figure 4).

Cross-cutting of selected trees 1, 3, 4, 6 and 8 (A-samples). Twenty-centimetre discs were cross-cut at 0, 2, 6, 10, 14 and 18 m stem height. The cross-cutting of discs was sometimes adjusted to avoid knots or other visible defects, which sometimes meant that the sampling height was slightly different ($<$20 cm) from the sampling plan (Figure 4). If a tree had a diameter of less than 7 cm at the intended sampling height no disc sampling took place at that height.

Cross-cutting of selected trees 2, 5 and 7 (B-samples). These trees were subject to the same sampling regime of discs as described for A-sample trees, with the exception that on the selected B-trees (tree 2, 5 and 7) a 70 cm stem bolt was cut instead of a 20 cm disc at 2, 6 and 10 m stem height.

From all sample trees (1–8) the cut stem discs/bolts were marked with the date, site, sample tree number, a line denoting northern exposure and height in the tree. They were then placed in plastic bags and transported to a freezer where they were kept until further sample preparation/measurements.

Modulus of elasticity of logs

After that tree stems had been cross-cut to generate stem discs and stem bolts according to Figure 1, the resulting logs (*c*. 1.8–4.0 m) were measured in length with a steel measurement tape to the closest 0.5 cm. Then, longitudinal resonance frequency was measured using a Rion SA-77 FFT signal analyser (Edlund et al., 2006) coupled with an accelerometer (Figure 2b). The logs were hit on the log end-surface with a hammer and the accelerometer picked up the signal pattern from the resonating log. The signal pattern was displayed with a graphical interface where a cursor was used to mark the peak position of the fundamental resonance frequency, which was recorded to the closest 10 Hz. Using the recorded log length (l), fundamental resonance frequency (f) and the assumption that Scots pine timber has a green wood density (ρ) of *c*. 800 kg m^{-3} (Nylinder, 1961), dynamic MOE was calculated using eq. (3):

$$\mathrm{MOE} = 4\rho l^2 f^2 \tag{3}$$

Equation (3) has been chosen because earlier studies have shown that stem bolts and logs exceeding a diameter:length ratio of 1:3 give reliable readings of resonance frequency (P. Harris, personal communication, August–September 2001). Moreover, validation studies have shown that dynamic MOE (calculated according to eq. 3) has high correlation with the MOE determined with static loading at 12% moisture content when using stem bolts exceeding a diameter:length ratio of 1:3 (Lindström et al., 2002, 2004). The correlation between dynamic and static MOE measurements is high, meaning that dynamic and static MOE denote the

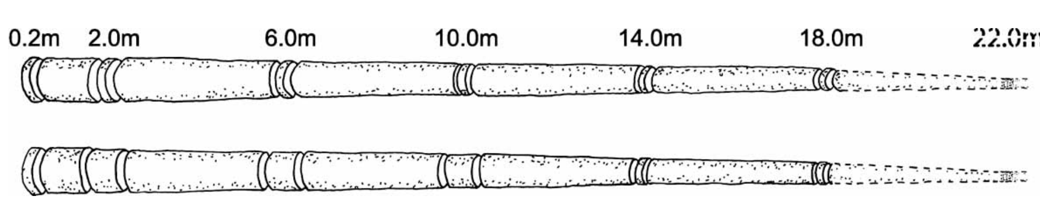

Figure 4. Cross-cutting points for disc and stem bolt samples. The cross-cutting pattern seen in the upper stem is representative of A-trees (sample trees no. 1, 3, 4, 6, 7) and the lower stem represents the cross-cutting pattern for B-trees (sample trees 2, 5, 7).

same property (material stiffness). This said, it has been noted that MOE values determined with acoustics yield systematically higher values than if determined with static loading (Ouis, 1999, 2002; Lindström et al., 2002; Huang et al., 2003).

Effects of site conditions and tree characteristics

The software packages used in calculations and statistical interpretation were Excel for Windows XP, the statistical software R v. 1.8 (Anon., 2003) and Matlab (Hanselman & Littlefield, 2005). A model (Model 1) of the MOE measured on standing trees (eq. 2) was developed using the transit-time data of the 189 sample trees. A second model (Model 2) was developed based on the MOE assessed with resonance-based technology (eq. 3) on 953 logs cut from the sample trees. Here, graphical modelling (Edwards, 2000) and stepwise regression were first used to screen possible models. Moreover, to avoid an overfit of the data to any of the models, the Schwarz information criterion (Schwarz, 1978) was employed. A set of models was developed with stepwise regression that used 3, 5, 7, 9 and all available variables. Finally, models (eq. 4) were constructed using variables that met the following model selection criteria: (i) variables should be significant at $p < 0.001$; and (ii) each model variable should add a partial $R^2_{\mathrm{adj}} > 0.01$.

$$(\text{Model 1}) = \sum_{i=1}^{k} a_i x_i + \varepsilon \qquad (4a)$$

$$(\text{Model 2}) = \sum_{i=1}^{k} b_i y_i + v \qquad (4b)$$

where a and b are the parameters, x and y are the explanatory variables, and ε and v are the residuals. The variables used in Models 1 and 2 can be seen in Tables III and IV.

Results

Modulus of elasticity assessed on standing trees

The MOE values derived from transit-time data for the southern and northern side of 189 individual trees are shown in Figure 3 and Tables I and II. Averaging the transit-time measurements from the southern and northern side on stems gave a calculated MOE variation of approx. 8.6–17.6 GPa (Figure 3, Table I) in the outerwood of standing trees. The more than two-fold variation in MOE of standing trees agrees with the MOE values on logs cut from similar tree height. Both results indicate large differences in MOE between trees (Table II).

The transit-time measurements on standing trees indicated that the regression slope is close to 1 (Figure 3), strongly indicating that MOE does not vary systematically with the southern or northern side of stems. The variation in impulse velocity, on opposite sides of the tree stems, is instead thought to represent differences in, for example, microfibril angle, knots, compression wood, grain deviations and/or wood defects.

Modulus of elasticity assessed on logs

The change in MOE at increasing stem height seen in Figure 6 indicates a pattern of increased MOE in the first approx. 2–4 m of a tree stem, then being held fairly constant, whereafter MOE decreases with increasing stem height. The observed MOE development with increasing stem height may reflect either (1) a cambial maturity phase in the first *c.* 1–5 m from stump height, i.e. cyclophysis (Olesen, 1982), which means that the vascular cambium will not have reached full maturity at lower stem height, and/or (2) that logs cut from successively higher stem positions (Figure 6) contain fewer growth rings, leading to more juvenile wood with high microfibril angle and low wood density.

Table III. Model variables.

Description of significant variables	
Growth condition and stand variables	
Site index	Site quality (H_{100}) (Gustavsen, 1980)
Tree variables	
dbh	Cross-calipered diameter at 1.3 m (mm)
Tree dominance	Eight trees that represented the diameter distribution were sampled within each stand and assigned number 1–8, where 1 = smallest tree, …, 8 = largest tree within the sample plot of each stand
Tree height	Tree height (dm)
D22A/B	Diameter between A and B diameter at 22 dm stem height
HighestDKnot	Highest dead knot height (dm)
Stem volume	The total stem volume of a tree (m^3 sk)
Log height	The stem height (m) that a log was cut from, using the calculated midpoint position of each log

Table IV. Modulus of elasticity (MOE) regression model of the 189 standing trees (Model 1) and on the 953 logs (Model 2).

Model	Criteria	No. of variables in model	R^2_{adj}	RMSE	b_{i-n}	*t* Value	X_{i-n}
1	(i) and (ii)	7	0.46	1.21	14.5663***	27.5605	Intercept
					−0.1163***	−5.9007	Site index
					−0.2329***	−8.8909	Tree dominance
					−0.0212***	−14.6725	dbh
					−0.0100***	−5.7904	D22A/B
					0.0264***	8.0146	Tree height
					0.0110***	5.0013	HighestDKnot
					2.6021***	7.5353	Stem volume
2	(i) and (ii)	5	0.62	1.20	8.1570***	33.7054	Intercept
					−0.1295***	−5.3665	Tree dominance
					−0.0055***	−5.8129	dbh
					−0.2128***	−33.8873	Log height
					0.0137***	7.2056	Tree height
					0.0149***	7.0935	HighestDKnot

Note: both models are based on selection criteria (i) and (ii), and best Schwarz information criterion (SIC), respectively.
***$p \leq 0.001$, **$p \leq 0.01$, *$p \leq 0.05$ (Anon., 2003).

Transit-time velocity and resonance-based assessments of modulus of elasticity

The agreement between the averaged transit-time data measured on the northern and southern sides of standing trees between 0.5 and 2.0m and the first, second, third, fourth, fifth, sixth and seventh log cut from the trees is shown in Table II. The results should be seen in the perspective that transit-time measurements will measure the MOE of the stiffer mature outerwood, while resonance frequency measurements will assess the average MOE for the entire log (Chauhan & Walker, 2006). In other words, Table II shows the correlation between the impulse velocity of outerwood in trees at low stem height and the MOE of logs cut from successively higher stem positions where the stem cross-section increasingly consists of juvenile wood. This may partly explain why there is high correlation ($r^2 = 0.72$) between the transit-time measurements on trees at 0.5–2.0 m and the MOE assessed with resonance frequency on the first logs (cut at *c.* 0.0–2.0 m), while there is successively weaker correlation between transit-time measurements and the MOE of logs cut from higher stem positions.

The variation in log MOE, assessed with resonance technology, on 953 logs cut from the 192 sample trees is shown in Figures 5 and 6 and Table I.

Statistics

The variables found to be significant in Models 1 and 2 (Table IV) indicate that the MOE development pattern with increasing tree height (Figure 6) would be influenced and overlaid by factors related to growth conditions, silviculture and tree characteristics. When interpreting the factors in Table IV that were found to have a significant effect on MOE, the main model interpretation is that trees that are tall relative to their diameter (relatively slender) are higher in MOE. Moreover, trees that have high

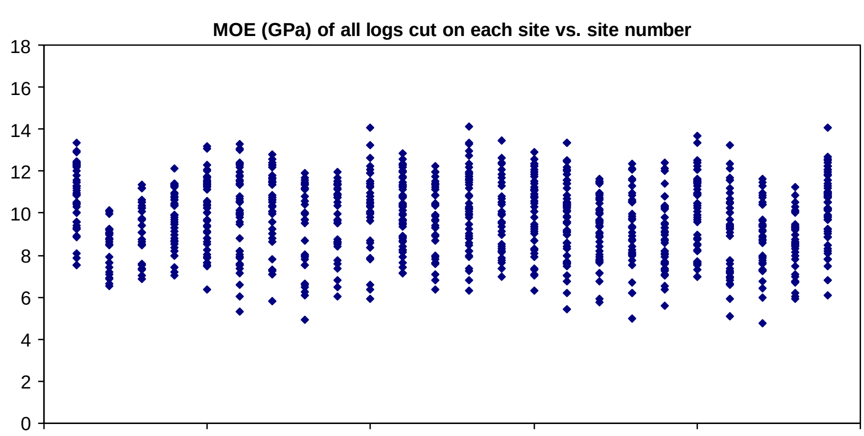

Figure 5. Variation in modulus of elasticity (MOE) of all 953 logs cut on sites 1–24.

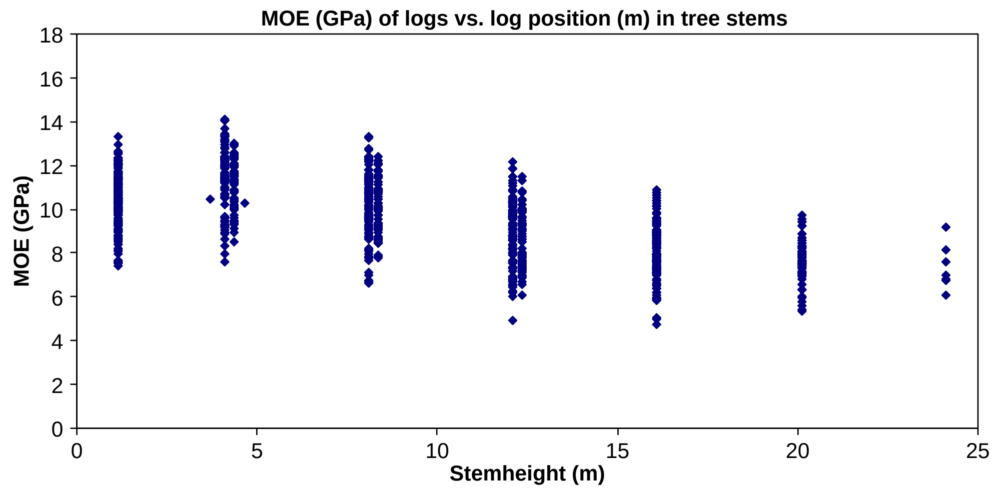

Figure 6. Modulus of elasticity (MOE) assessed with resonance frequency on the 953 logs sampled at increasing stem height from 192 sample trees. Note that the cross-cutting patterns of A and B logs give a systematic difference in log sampling position and that two logs were cut slightly off the intended sampling position.

onset of their first visible dead knots will have higher MOE. According to the derived models, trees are more likely to have high MOE if they (1) are non-dominant in the stand; (2) are tall in relation to diameter (have low taper); (3) have a high onset of visible dead knots (due to crown competition); (4) have a high stem volume (mature older trees); and (5) have a circular stem cross-section.

Similar results have been reported for *Pinus radiata* by Watt et al. (2006). For instance, there seems to be a negative effect on MOE of increasing tree dominance. In contrast, trees that are tall relative to their diameter (often seen in trees that experienced moderate–high crown competition) seem to have higher MOE. To generalize these findings would be difficult; however, the results clearly indicate that the forest management method will have a considerable influence on the MOE in Scots pine tree stems. That is, if within-stand tree competition is kept reasonably high during the establishment phase of a new forest it would result in trees having less vigorous branches and smaller living knots, and also that tree crowns would be higher set, meaning less stem taper and higher stem MOE. If, instead, trees were allowed to be free growing and dominant from an early age, this would result in trees with high stem taper and low stem MOE.

Discussion

The material used in the study

Although the selection of stands and trees in this study was designed to cover as much variation in growth conditions as possible, it is still rather limited material. Therefore, it is assumed that the natural MOE variation of Scots pine trees in southern and central Sweden would be even larger than the considerable variation seen in the descriptive data That is, MOE assessed with transit-time technology on standing tree stems at 0.5–2.0 m was found to be approx. 8.6–17.6 GPa. MOE assessed with resonance-based technology varied between 7.4 and 14.1 GPa for logs cut at similar height (2.0–6.0 m).

Transit-time and resonance-based modulus of elasticity assessments

The first hypotheses of this study was to explore the possibilities of using acoustic measurements to assess the MOE of trees as a non-destructive method to determine wood quality of trees and logs in the field. The methods were found to be reliable, apart from tests made on standing trees on stony soils during heavy windsway. Moreover, it should be noted that measurements were undertaken in summer and that the acoustic tools may work differently when used at lower temperatures.

Using transit-time technology, large differences in impulse wave velocity were observed on the southern versus northern side of some trees (Figure 3). No systematic difference in impulse wave velocity could be seen when comparing the impulse velocity data for the southern versus northern side of all trees. Instead, large variation in impulse wave velocity in diametrically opposed stem sectors of individual tree stems was interpreted as local defects and/or wood structure differences. As the within-tree variation in MOE (impulse velocity) seems more pronounced in low MOE trees (Figure 3) it may be that such trees, on average, have larger wood variability or knots/ defects within the tree stem compared with high MOE trees. However, more detailed studies would be necessary to determine the relationship between impulse wave velocity and wood defects.

The agreement obtained between transit-time technology and resonance-based technology is higher when comparing MOE assessments obtained at similar height, while the correlation seems to decrease when comparing transit-time data with the resonance-based data obtained from logs further up a tree stem (Table II). For instance, the variation in MOE assessed by resonance technology on short logs cut at 0.0–2.0 m stem height largely follows the MOE assessed with transit-time technology at 0.5–2.0 m on standing trees. However, the transit-time measurements are inherently giving higher values of MOE as the highest impulse wave velocity is found in the mature outer wood, whereas resonance-based technology averages the MOE for the entire wood volume of a log (Chauhan & Walker, 2006). It should be noted that there was no measurement of green density in this study. It was merely assumed that the green density of fresh Scots pine timber is equal to 800 $kg\,m^{-3}$. As the sapwood is probably closer to 1000 $kg\,m^{-3}$ and some logs may have lower green density, i.e. about 700 $kg\,m^{-3}$, according to Nylinder (1961), there may be an underestimation or overestimation of the assessed MOE by $\pm$10–25%. If actual measurements of green density had been done, giving more precise assessment of density in eqs (2) and (3), it would have amplified the systematic differences between the MOE found in the outer mature wood measured by transit-time technology (eq. 2) and the MOE assessed for an entire log using resonance frequency measurements (eq. 3).

A height-dependent modulus of elasticity pattern?

From the appearance of Figure 6 and from the statistical analysis it seems as though there might be a height-dependent MOE pattern: an initial increase in MOE, followed by a more or less constant MOE, then a gradual decline with increasing stem height (Figure 6). Similar results have been obtained by Xu and Walker (2004), which argues that there may indeed be a height-dependent MOE pattern. Still, it came as a surprise that an MOE development pattern also seems to exist for the studied trees, as they were sampled from forests with varying site index and/or belong to differing tree classes. Further research in this area is recommended to understand whether and why a height-dependent MOE pattern exists.

Until then, the observed change in MOE with increasing height is assumed to depend on a complex interaction between genetics and growth conditions of an individual tree. For instance, it has been argued that the vascular cambium has a genetically predetermined wood structure formation that is modulated by the windload of a tree stem. The survival of a tree relies on the stem wood structure being able to withstand wind failure and breakage (Schwendener, 1874; Mattheck, 1991; Watt et al., 2006). The distribution of windload and its displacement on to the cross-stem section mean that the tree adjusts the wood stiffness to be highest in the last formed growth rings in the stem section situated close to the midpoint of the living tree crown, where maximum strain occurs. This has been indirectly corroborated by studies showing that the longest tracheids can be found in the last formed growth rings at the onset of the living crown (Atmer & Thörnqvist, 1982). It should be noted that long tracheids have lower microfibril angle (Albert et al., 2002; Lindström et al., 2005), causing higher MOE of wood (Cave, 1968, 1969; Cave & Walker, 1994; Lindström et al., 2002; Huang et al., 2003). From this perspective, it would be possible to model MOE development in a tree stem based on factors that regulate or mirror crown size and windload distribution. However, such factors only explain part of the MOE variation, as genetic differences will also strongly influence the MOE of wood in conifer trees (Lindström et al., 2004, 2005).

Model interpretation

The developed models indicate that it is possible to predict the MOE of trees and logs by using factors related to tree growth. According to the models it seems likely that forest management regimes that aim for tall, slender trees with high set crowns will on average produce trees with higher MOE. It is assumed that the variables that were found to be significant in the derived models, e.g. tree dominance, stem taper, tree height, knot placement and knot size, mirror the historic growth conditions of individual trees. The MOE models derived from factors related to growth conditions at stand and tree level had quite low explanation: $0.46 < R^2_{adj} < 0.62$, which underlines the problem of using prediction models of MOE based on factors related to growth conditions. However, there seem to be plenty of exceptions from the outline above, which are probably due to genetic differences and complex interactions that go beyond the scope of this explorative study.

Using more extensive material, in future studies, may provide better modelling opportunities that would yield more sophisticated models with higher prediction ability. Models of tree and log MOE could then guide the strategic selection of trees suitable for a given range of solid wood products.

Such models could also be used when designing silvicultural strategies that yield trees with high MOE. Another opportunity to predict and assess MOE and wood properties could lie in the future development of non-destructive measurement technologies. This could involve taking MOE measurements on standing trees at the time of thinning and/or at final tree harvesting. Such information could be used to reduce the number of logs with unsatisfactory wood properties that eventually arrive at the sawmill.

Conclusion

This study shows that there is large variation in MOE between and within *P. sylvestris* trees and that the MOE development and variation are linked to growth conditions and tree characteristics. The derived models suggest that forest management regimes that aim for tall trees with low stem taper would yield trees with a high MOE.

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