MODULUS OF ELASTICITY OF STEMWOOD *VS* BRANCHWOOD IN 7-YEAR-OLD *PINUS RADIATA* FAMILIES

LINDA C.-Y. HSU, SHAKTI S. CHAUHAN

School of Forestry, University of Canterbury,
Private Bag 4800, Christchurch, New Zealand

NICK KING

Cawthron Institute,
Private Bag 2, Nelson, New Zealand

and HÅKAN LINDSTRÖM

School of Forestry, University of Canterbury,
Private Bag 4800, Christchurch, New Zealand

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ABSTRACT

Thirty-six 7-year-old trees representing three families of *Pinus radiata* D.Don were selected within a replicated block family trial. Stem bolts were taken from three stem positions up each tree — at approximately 1.4 m, and at 50% and 80% of total tree height. The three largest branches in the whorl immediately above each sampled stem bolt were sampled and analysed using the first three branch internode segments, both individually and collectively. A resonance-based system was used to measure dynamic modulus of elasticity (MoE) of branchwood and stemwood green and at 12% moisture content (m.c.).

The volume-weighted stem modulus of elasticity and the stem bolt modulus of elasticity at 1.4 m were highly correlated (r = 0.95). Individual branch segments cut from the largest-diameter branch in the whorl immediately above the lowest stem bolt position showed highest correlation with stem modulus of elasticity. Utilising a set of branch segment criteria, the best linear model of stem bolt modulus of elasticity at 12% m.c. ranged between R^2Adj = 0.51 and 0.62, with a residual mean square error (RMSE) varying between 0.36 and 0.42 GPa.

Keywords: genetics; modulus of elasticity; wood variation; branch wood; *Pinus radiata*.

INTRODUCTION

With old-growth forests being successively replaced with plantation forests, the forest industry has become increasingly aware of the intrinsic variability of wood from fast-grown conifer trees. Increasing efforts on log segregation and refined production processes

(Sandberg 1996; Haslett & Dakin 2001; Tsehaye *et al.* 2000a,b) are seen as viable approaches to address this wood variability.

As the high proportion of corewood obstructs efforts to maintain consistent quality of forest products (Kretschmann & Bendtsen 1992; Kennedy 1995), tree breeding has increasingly focused on the possibility of selecting trees that have better corewood quality (Shelbourne *et al.* 1997; Sorensson *et al.* 1997). In other words, a long-term solution is to propagate trees that have better juvenile wood properties, i.e., similar to those found in more mature wood further from the pith (Zobel & Buijtenen 1989; Shelbourne *et al.* 1997; Jayawickrama & Jefferson 1999; Walker & Nakada 1999). For instance, the value of construction wood, a large component of total sawmill production, correlates strongly with its stiffness and form stability. Consequently, the selection and breeding of trees that have higher modulus of elasticity (MoE) combined with low warp propensity would mean higher future revenues for solid wood products.

In recent years, acoustic tools have been used to classify and select logs and trees with higher modulus of elasticity (Marchal & Jacques 1999; Walker & Nakada 1999; Lindström *et al.* 2002; Wang *et al.* 2001, 2002). Modulus of elasticity is a composite function of microfibril angle and basic density which makes it a very robust selection trait (Evans & Ilic 2001; Lindström *et al.* in press). These studies show that there is:

(a) a high correlation between static modulus of elasticity and dynamic modulus of elasticity of stem bolts;

(b) a large variability in modulus of elasticity between clones of young *P. radiata*.

Because resonance-based acoustic tools can be used conveniently to determine the modulus of elasticity of irregularly-shaped wood samples, it was considered that branch modulus of elasticity could be used as a non-destructive indicator of stemwood properties in tree breeding trials. For instance, earlier studies indicated a correlation between branchwood and stemwood properties in terms of tracheid length (Sudo 1973; Fujisaki 1978, 1983) and stem MoE (Taira *et al.* 1990; McAlister *et al.* 2000). The available literature also indicated that the agreement of branch and stem modulus of elasticity would rely on a set of sampling factors, e.g., whether branchwood samples were taken from the upper or lower side of the branch (Park *et al.* 1979), or whether growth stresses were present in the selected branches (Yoshida *et al.* 1992).

In this scoping study to explore methodologies, three families of *P. radiata*, using 12 trees per family, were selected:

- to determine the correlation between stemwood and branchwood modulus of elasticity at breast height, and
- to derive a model that indicates the potential of branchwood modulus of elasticity as a predictor of stemwood modulus of elasticity.

MATERIAL AND METHODS

Initial Selection of Three *P. radiata* Families

The trees used in this study were part of a seed production trial selected on the basis of good growth and stem form. The trial was established by Proseed New Zealand Ltd in the South Island of New Zealand, close to Amberley, North Canterbury, in 1994. Full-sib families were planted in 16 randomised blocks with one four-tree row plot per block. Three families were taken to represent modulus of elasticity family variability in the trial, and 12 trees with no visible defects or stem injuries were felled from each selected family using six blocks in the trial. The family average diameters at breast height are listed in Table 1.

TABLE 1–Diameter, stiffness, and density of the 36 trees from the three studied families.

Family number	Dbh* (mm)	First bolt location† (m)	First bolt MoE‡ (GPa)	First bolt density at 12% m.c.§ (kg/m³)	Stem MoE‖ (GPa)	Stem density at 12% m.c.‖ (kg/m³)
1	116	1.3–1.8	4.6	411	4.9	409
2	111	1.3–1.8	4.4	409	4.9	408
3	103	1.5–2.0	5.0	412	5.3	411
Min	71	0.7–1.0	3.5	383	3.9	385
Max	137	2.8–3.3	6.2	458	6.4	450
$\text{Family}_{\text{Mean}}$	110	1.4–1.9	4.7	411	5.0	409
Estimated LSD¶	13.6	0.44–0.47	0.55	14.4	0.49	13.4

* Average diameter for each family assessed from average diameter of the first bolt sampling position.
† The averaged lower-upper sampling position of the first position stem bolt (Fig. 1) for each family.
‡ Average family MoE (12% m.c.) measured with WoodSpec on stem bolts taken from the first bolt sampling position.
§ Density of first position stem bolt at 12% m.c.
‖ Volume weighted average of the three bolts, sampled from each tree (Fig 1).
¶ Fisher's least-significant-difference (LSD) test between family means. Estimated LSD values based on three comparisons.

Stem Bolt Sampling

Clearwood bolts cut from three stem positions as well as the top shoot (above all lateral branches) were sampled from the 36 selected trees. Bolts were taken at approximately breast height (1.4 m), and at 50% and 80% of total stem height. The spacing and position of branches created difficulties in cutting bolts near breast height. Also, because all sampled bolts had to have a length-to-diameter ratio of at least 3 (a requirement for acoustic velocity measurement with WoodSpec), the sampling height position of the lowest stem bolt sometimes differed substantially from 1.4 m. The length of the bolts taken at breast height ranged from 0.32 to 0.80 m. In total, there were 108 stem bolts and 36 top shoots (Fig. 1). All sampled bolts/shoots were marked with plot, family, tree number, and position.

Branch Sampling

The three largest branches were taken from the branch whorl immediately above each stem bolt. In total, 324 sampled branches (3 families × 12 trees × 3 positions × 3 branches) were marked with plot, family, tree number, and position within tree.

Storage, Preparation, and Dynamic MoE Measurements

Immediately after felling, stem bolts and branches were placed in a freezer store to prevent water loss.

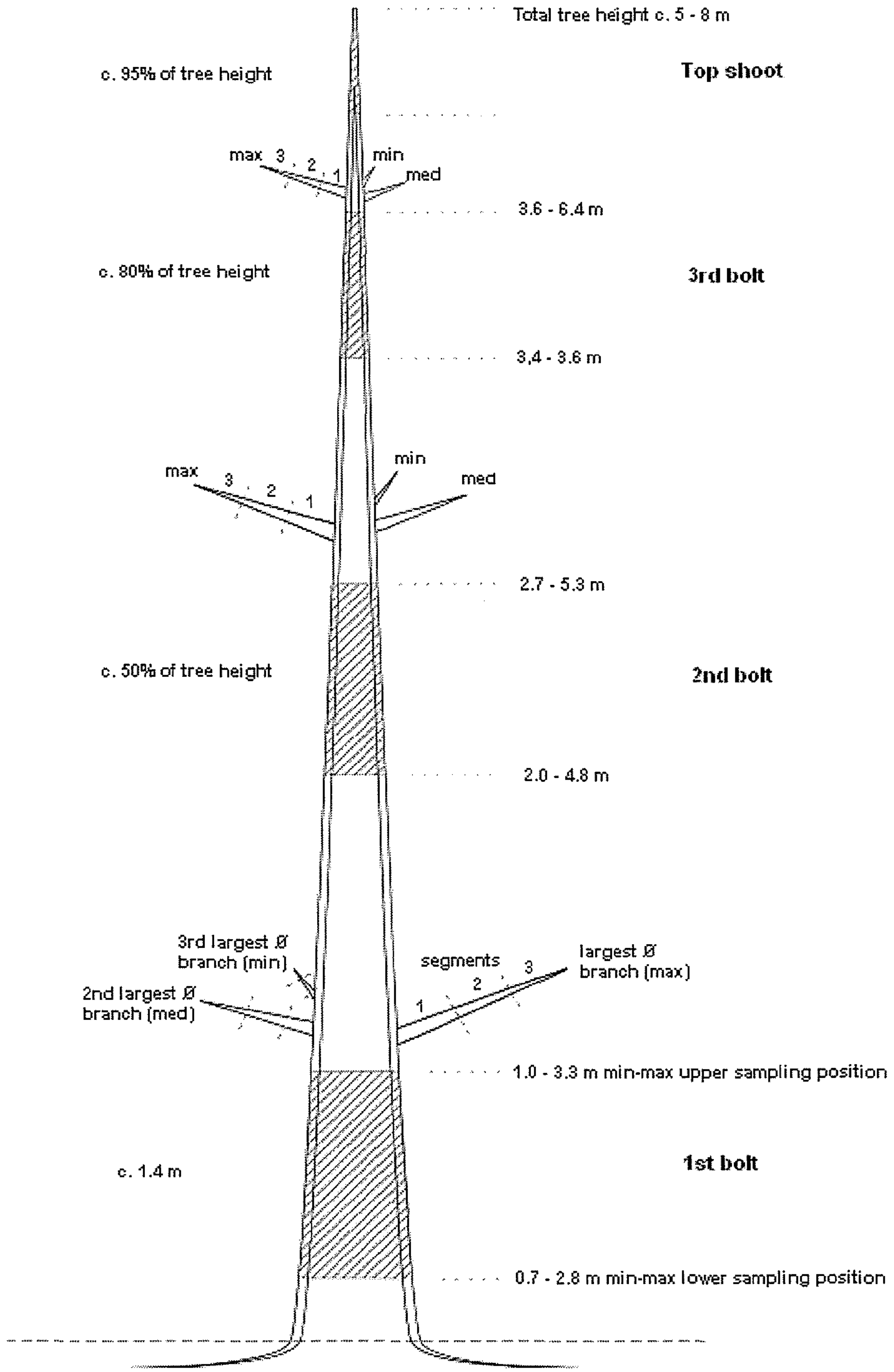

FIG. 1–The sampling positions of bolts, top shoots, and branches within each tree.

Measurement of stem bolts

Before any properties were measured, the bolts were thawed at room temperature and then re-cut with a circular saw to give a test sample with a minimum diameter:length ratio of 1:3 with smooth parallel end-surfaces.

WoodSpec, a resonance-based system (Lindström *et al.* 2002), was used to measure the dynamic modulus of elasticity of stem bolts green and at 12% m.c. With resonance, the stress wave travels back and forth along the sample (i.e., the distance is twice the sample length) at a velocity that can be determined from the recorded frequency spectrum. For the fundamental frequency, f, the velocity is given by:

$$V = 2\,l * f \tag{1}$$

where f (Hz) is the fundamental resonance frequency and l (m) is the sample length.

The modulus of elasticity of a material is calculated from the equation

$$MoE\ (Dynamic) = \rho\, V^2 \tag{2}$$

where ρ (kg/m^3) is the density of the material and V (m/s) is the acoustic velocity.

Solving both Equations (1) and (2) one obtains:

$$MoE\ (Dynamic) = 4\,\rho\, l^2 f^2 \tag{3}$$

The calculated green density was based on water displacement of green bolts where the volume was determined to ±0.5 cm^3 and the green stem bolt weight determined to ±0.5 g. The stem bolts were then dried in an air-conditioned room (25°C, 65% RH) to 12% m.c. and re-measured for acoustic velocity. To measure density of bolts at 12% m.c., the dry stem bolt weights were determined to ±0.5 g before and after brushing with liquid silicone to prevent water absorption during water displacement. The dry volume was determined to ±0.5 cm^3. Density of the bolts at 12% m.c. was then calculated. The family average modulus of elasticity based on the bolts at approx. 1.4 m stem height is given in Table 1.

Measurement of branches and internode segments

Branches were thawed at room temperature and the acoustic velocity was measured using WoodSpec. Each branch was then cut into three internodal branch segments (first, second, and third from the stem) (Fig. 1). In theory, this should yield 972 branch segments (3 × 324). However, only 743 branch segments were generated; some branches, especially those at higher sampling positions, had only one or two branch segments.

The acoustic velocity of each segment was measured twice, once with bark and once without (Fig. 2). Weight of green branches was determined to ±0.05 g. Volume of the branches in green condition and of the segments was obtained by water displacement to ±0.5 ml.

All branch segments were then placed in an air-conditioned room (25°C, 65% RH) to equilibrate at 12% m.c. and re-measured for acoustic velocity. Weight of dry branches was determined to ±0.05 g. The dried branch segments were lightly brushed with liquid silicone to prevent water absorption. Then the volume of the branches in green condition and of the segments was obtained by water displacement to ±0.5 ml. The modulus of elasticity of branch segments was calculated green and at 12% m.c.

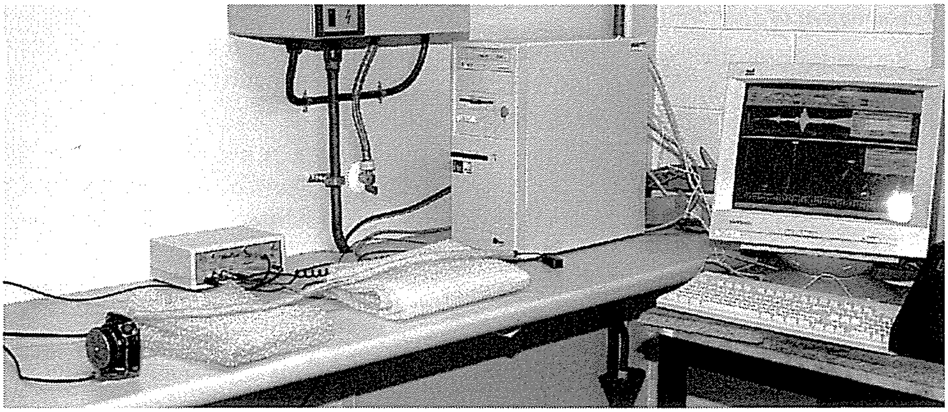

FIG. 2–The acoustic tool "WoodSpec" used for modulus of elasticity measurement of stem bolts and branch segments.

RESULTS

Average Family MoE and Density for Stem Bolts

Modulus of elasticity was measured green and at 12% m.c. for the top shoot, the three internodal stem bolts (Fig. 1), and the first three branch segments of the three largest branches from the whorl immediately above each sampled stem bolt. The volume-weighted average modulus of elasticity for the stem bolts of each family are given in Table 1.

The SAS t-test procedure (SAS Institute 1998) using Fisher's least-significant-difference (LSD) test was used to explore differences between family means for density, modulus of elasticity, and stem bolt sampling positions. No significant difference in density between families was seen. One family seemed to have a slightly higher modulus of elasticity than the other two. However, this may not be a real difference, as the modulus of elasticity of bolts increased at least up to approx. 4 m stem height (Fig. 3) and the first bolt of the highest modulus of elasticity family was sampled at a slightly higher position (1.5 m) than the other two families (1.3 m). This unequal sampling height is believed to be a consequence of the branching habit of each tree and/or family and the requirement that each sampled bolt should have a diameter:length ratio of at least 1:3. The progressive change in stiffness with increasing stem height was not part of the research objectives for this study.

However, the trend of modulus of elasticity increasing up the stem to approx. 3–4 m in young *P. radiata* was obvious both in this study based on 7-year-old trees taken from three families and in a clonal field trial of four 7-year-old trees of the same clone at Burnham, 30 km west of Christchurch on the Canterbury Plains (unpubl. data) (Fig. 4). In the clonal field trial, stiffness was observed to increase by approx. 0.6 GPa/m between 1 and 4 m stem height (Fig.4), and for the three families (Fig.3) stiffness increased at a rate of 0.3–0.5 GPa/m. Therefore, the wood in the third growth ring at breast height would be less stiff than the wood in the third growth ring higher in the tree stem. Such results indicate that adjustment to equal sampling height is crucial for an objective comparison of stemwood modulus of elasticity of trees.

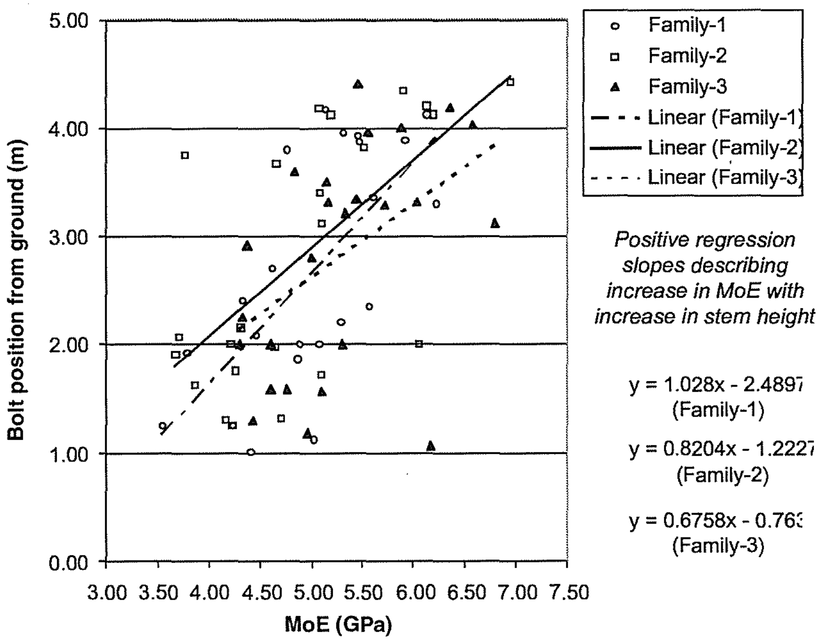

FIG. 3–Modulus of elasticity at 12% m.c. of stem bolts *vs* the sampling position of bolts within trees. The approximate stiffness increase in these three families is close to 0.75 GPa/m between 1 and 4 m stem height.

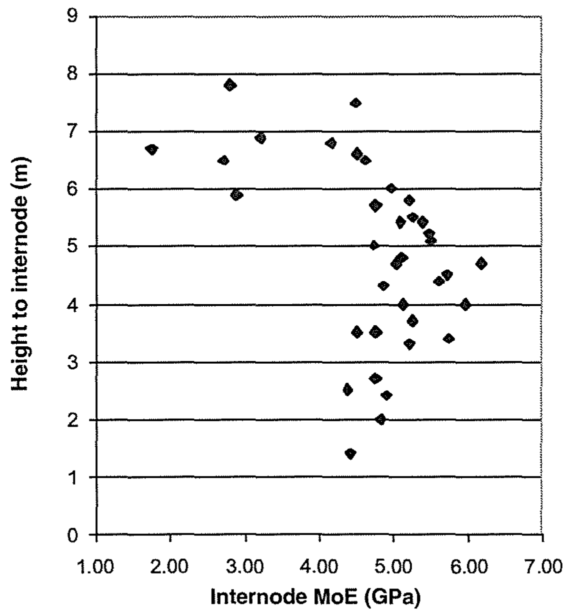

FIG. 4–Unpublished data on the development of MoE with increasing height in four 7-year-old *Pinus radiata* trees of the same clone. The approximate stiffness increase in this single clone is close to 0.5 GPa/m between 1 and 4 m stem height.

Correlation Between Stem and Branch/Top Shoot Modulus of Elasticity

Stem bolts and branch segments

The modulus of elasticity of bolts taken at less than 3 m stem height and the stem volume-weighted modulus of elasticity (using data from the three sampled stem bolts measured at 12% m.c.) of these trees showed a very high correlation (r = 0.95). So it was judged that one only needed to sample stem bolts from a stem position less than 3 m high to construct a viable model. The correlations between the modulus of elasticity of stem bolts and each of the three dissected branch segments were explored. To reduce the effect of possibly unreliable acoustic modulus of elasticity readings from small length/diameter branch segments, while still retaining a reasonable number of branch segment observations, further criteria were included to construct more accurate models.

Qualifying branch segment criteria:

(a) Each model to be based on branch segments from the largest-diameter branch immediately above the lowest stem bolt (Fig. 1);

(b) Branch segment to be ≥25.0 cm long (Fig. 1);

(c) Branch segment diameter to be ≥1.0 cm (Fig. 1).

The highest single branch segment correlation, using the selection criteria in (a) – (c), was found between the modulus of elasticity at 12% m.c. of the first bolt position and the modulus of elasticity of the first bark-free branch segment in green condition (r = 0.74, n = 26, Fig. 5).

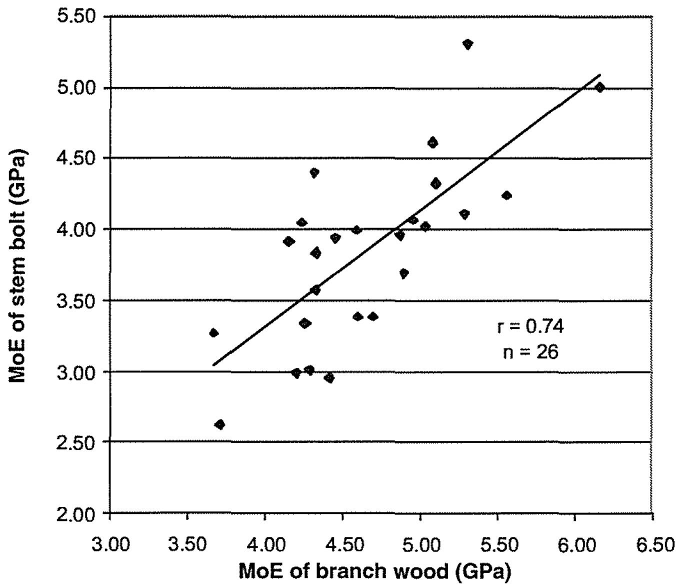

FIG. 5–A scatter plot of the highest correlation (r = 0.74, n = 26) found between the MoE at 12% m.c. of the first bolt position and the MoE of the first bark-free branch segments in green condition, using the selection criteria in (a)–(c).

Two model criteria were considered:

(1) Modulus of elasticity of bolts at less than 3 m stem height *vs* the modulus of elasticity of branch internode segments that met the criteria (a) – (c) and that were found closest to the stem. The coefficient of determination and RMSE of the best model using bark-free branch segments green and at 12% m.c. are shown in Table 2;

(2) Modulus of elasticity of bolts at less than 3 m stem height *vs* the modulus of elasticity of the branch segment that met the criteria (a) – (c). If there was more than one segment that met these criteria, then the selected branch segment was the one with the highest modulus of elasticity. The best model using bark-free branch segments green and at 12% m.c. is shown in Table 2.

TABLE 2–Coefficient of determination and RMSE for Models (1) and (2) based on the qualifying branch segment criteria (a)–(c). Number of observations (n) fulfilling the criteria for each model are given in the table. Model (3) is based on top shoots.

Regression equation	n	R^2Adj	a	sa	b	sb	RMSE
1 (a) $Y = a + bx + \varepsilon$ (branches at green m.c.)	25	0.53	2.37***	0.50	0.68***	0.13	0.41 GPa
1 (b) $Y = a + bx + \varepsilon$ (branches at 12% m.c.)	26	0.61	2.25***	0.44	0.55***	0.09	0.36 GPa
2 (a) $Y = a + bx + \varepsilon$ (branches at green m.c.)	25	0.51	2.28***	0.54	0.69***	0.14	0.42 GPa
2 (b) $Y = a + bx + \varepsilon$ (branches at 12% m.c.)	26	0.62	1.94***	0.48	0.60***	0.09	0.36 GPa
3 (a) $Y = a_+ bx + \varepsilon$ (topshoots at green m.c.)	36	0.03	4.12***	0.64	0.29	0.20	0.68 GPa
3 (b) $Y = a + bx + \varepsilon$ (topshoots at 12% m.c.)	35	0.07	3.63***	0.77	0.31	0.17	0.67 GPa

*** indicates $p \leq 0.001$.
"a" and "b" are the regression coefficients and "s_a" and "s_b" are the standard errors of estimated regression coefficients respectively.

Stem bolts and top shoots

Above all lateral branches, the modulus of elasticity of the top shoot of each tree was determined but, as can be seen in Table 2, the attempt to model stem modulus of elasticity based on the top shoot modulus of elasticity (Model 3) was unsuccessful. It is possible that both unequal sampling positions of top shoots from trees of unequal height and unequal maturity of top shoots might have contributed to this result.

DISCUSSION

Short Rotation Forestry — Wood Properties

A fundamental problem associated with the lower stockings and shorter rotation age in modern forest management is the increased proportion of juvenile wood with high wood variability. Given that short rotations are of primary interest in commercial forestry to sustain profitability, it will be necessary to select trees that have better juvenile wood properties. For instance, acoustic tools can screen for trees with high modulus of elasticity which could give the option of breeding for trees with juvenile wood that has a high modulus of elasticity mainly as a result of low average microfibril angle (Fujisawa 1998; Lindström *et al.* 2002, in press). An improvement in the juvenile wood properties implies that the forest industry in the future could be based on trees that, despite being fast-grown, will yield sawn lumber with satisfactory end-use properties, e.g., lumber with consistently high modulus of elasticity and low drying distortion even in the juvenile wood zone.

Material and Results

While tree breeding sometimes includes density as a selection trait, it would probably make more sense to include modulus of elasticity assessment as a basis for selecting trees with better average wood quality. Modulus of elasticity has been found to be dependent on the average wood structure variability in terms of microfibril angle and wood density (Evans & Ilic 2001; Lindström *et al.* 2002, in press). Moreover, modulus of elasticity is commonly used as an objective description of the quality or commercial value of sawn lumber.

The main purpose of this scoping study was to explore the possibility of selecting trees for inclusion in tree breeding programmes using non-destructive modulus of elasticity assessment. The approach was to study the correlation of stem modulus of elasticity with branch modulus of elasticity, with a view to using branchwood rather than having to rely on destructive sampling of stemwood. The results indicate a medium to high correlation between the two, implying that branch modulus of elasticity can be used to rank trees; the effectiveness of branchwood modulus of elasticity in predicting stemwood modulus of elasticity is illustrated in Fig. 5. However, as there is a range of transit time tools available that can be applied nondestructively to measure the stem modulus of elasticity of standing trees with adequate or high precision (r^2 = 0.65–0.95, Tsehaye *et al.* 2000a, b; Lindström *et al.* 2002; Wang *et al.* 2001, 2002), the practical use of ranking trees according to their branch modulus of elasticity will need further consideration.

Although the current study exhibited a small but statistically significant difference in modulus of elasticity (4.4–5.0 GPa) between the three studied families, this might merely reflect slightly differing heights of bolt sampling. Then again, the small differences in modulus of elasticity between families might also reflect the limited number of families (n = 3) available in this study.

CONCLUSIONS

This scoping study shows that a reasonable correlation exists between branchwood and stemwood which would permit non-destructive modulus of elasticity assessment of standing trees. However, it is already known that non-destructive measurement of acoustic velocity is capable of ranking standing trees for modulus of elasticity and it is not clear whether branch sampling would prove a viable option.

One important outcome of this study was that the results highlighted the need to measure modulus of elasticity over a defined stem height and to determine the stiffness gradient in the first few metres of young stems to allow for adjustment to equal sampling height and fair comparisons of stem modulus of elasticity.

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