IMPLICATIONS OF SELECTING TREE CLONES WITH HIGH MODULUS OF ELASTICITY

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ABSTRACT

To obtain shorter rotation periods for *Pinus radiata* D.Don, forestry management has an underlying economic incentive to achieve faster tree growth. However, faster tree growth paired with short rotation time implies that sawmills will increasingly use timber containing high amounts of juvenile wood that results in low stiffness and considerable drying distortion of the sawn lumber. A long-term solution to improve solid wood properties of fast-grown conifer trees would be to select and breed trees in which the juvenile wood has a higher modulus of elasticity and lower wood property gradients in the radial direction.

This study was limited to select clone material thought to represent the approximate boundaries for wood property gradients in the juvenile wood of young *P. radiata* clones. A lower microfibril angle and slightly larger tracheid dimensions could be found in the juvenile wood of clones with high modulus of elasticity than in clones with low modulus of elasticity. This suggested that in clones with high modulus of elasticity there is a smaller wood property gradient in the transition from juvenile to mature wood which would make drying distortion, for example, less pronounced in lumber sawn from high modulus of elasticity timber.

Keywords: tree clones; wood quality; wood properties; modulus of elasticity; density; microfibril angle; fibre length; fibre dimension; *Pinus radiata.*

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INTRODUCTION

Fast Tree Growth Creates Problems for the Sawmill Industry?

In comparison with hardwood lumber, softwood timber has the advantages of being easy to saw, dry, transport, reshape, and assemble while having excellent rigidity and strength properties in relation to weight. These material properties, paired with low cost, have made softwood lumber a preferred material for general construction. However, to maintain or improve financial returns, commercial forestry aims at faster tree growth and shorter rotations. This implies that the juvenile wood content in timber used for sawmilling is bound to increase (Thörnqvist 1993; Kennedy 1995; Walker 2000). Increased juvenile wood content in sawlogs would mean that the proportion of lower grade lumber in the sawmilling industry increases in both absolute and relative terms. For instance, sawn lumber with high proportions of juvenile wood is known (Kretschmann & Bendtsen 1992; Cave & Walker 1994; Burdon *et al.* 2004) to have lower modulus of elasticity (MOE) and create substantial drying distortion (Kyrkjeeide *et al.* 1994; Persson 1997; Ormarsson 1999) compared with lumber produced from slower-grown trees in which the juvenile core is smaller.

One way to reduce the problems associated with fast-grown timber is to use more sophisticated log sorting where logs with unsuitable material properties are simply not used to produce lumber (Tsehaye *et al.* 2000) There is also the possibility of using improved production processes and refined sawing patterns (Sandberg 1998) in order to reduce drying distortion. However, such solutions are viable only if the product can bear the additional cost of sophisticated log sorting and/or modified processing and still maintain the necessary profit margins (Perstorper 1994; Walker 2000).

A Long-term Solution: Changing the Properties of Juvenile Wood

Tree breeding could provide a long-term solution to improve stiffness and drying distortion of construction lumber (Lindström *et al.* 2004). The aim would be to select trees with juvenile wood properties more similar to those found in mature wood. It may be possible to base such breeding attempts on modulus of elasticity as substantial differences in fibre properties have been observed among pulp logs with differing modulus of elasticity (Albert *et al.* 2002). That way, forest management could promote fast tree growth through the use of intensive silvicultural methods while minimising adverse effects on wood quality.

To obtain a genetic improvement of solid wood properties one main target would be a reduction in the within-tree wood gradients, i.e., the differences in wood properties between juvenile and mature wood (Barrett *et al.* 1972; Walker & Butterfield 1996; Persson 1997; Forsberg 1999; Dickson & Walker 1997; Ormarsson

1999). A tree breeding programme designed to reduce wood property differences between juvenile and mature wood would include traits such as:

- Spiral grain (minimise in juvenile wood)
- Microfibril angle (minimise in juvenile wood)
- Lignin content (decrease in juvenile wood)
- Wood density (increase cell wall thickness in juvenile wood without increasing compression wood).

These key traits may be inter-related, but a combined selection in tree breeding programmes should result in lower contrast between juvenile and mature wood which would mean improved timber quality. That is, appropriate tree selection using these traits would yield trees that are genetically more suitable for structural lumber production.

Can Wood Property and Wood Shrinkage Gradients be Reduced by Breeding Trees with High Modulus of Elasticity?

Several studies have argued that acoustic methodology can be used to select and breed trees that have higher modulus of elasticity in the juvenile wood (Walker & Nakada 1999; Huang *et al.* 2003; Lindström *et al.* 2004). As modulus of elasticity is a reflection of the underlying wood properties (spiral grain, microfibril angle, lignin content, and wood density) a change will have an effect on volumetric and directional shrinkage of wood. For instance, according to Cave (1978) the volumetric shrinkage (ε°) of wood is equal to the volume of released bound water (W_b) by:

$$\varepsilon^{\circ} = W_b = b \, \frac{1 - e^{-\frac{wk}{b}}}{1 - e^{-\frac{0.3k}{b}}} \qquad (1)$$

where b is the amount of bound water at saturation, $w = 0.3$. The constant k is set to 0.9. As crystalline cellulose is not considered to absorb water, the change in ε° could be written as:

$$\Delta\varepsilon^{\circ} = f_H \Delta W_{bH} + f_L \Delta \mathrm{W}_{bL} \qquad (2)$$

where $f_H \Delta W_{bH}$ and $f_L \Delta \mathrm{W}_{bL}$ represent water bound to hemicelluloses and lignin respectively. Selecting trees with higher modulus of elasticity implies an indirect selection for trees with lower average microfibril angle and lignin and hemicellulose content while the cellulose content would be higher (Albert *et al.* 2002) reducing the amount of water bound to the tracheid cell wall (i.e., the wood saturation point) and therefore the potential for volumetric shrinkage. Moreover, as wood shrinkage can be considered a result of the dehydration of mainly hemicelluloses in the tracheid cell walls, directional shrinkage should be a direct response to those wood variables that describe the 3-dimensional storage of bound water:

(a) Average microfibril angle, defined as the average orientation of cellulose molecules in the cell walls of wood tracheids, relative to the average direction of the tracheid axes (Navi *et al.* 1995);

(b) Tracheid dimensions, and relative thickness of the lamellas in the secondary cell wall;

(c) Content and topochemical composition of hemicelluoses and lignin;

(d) Tracheid orientation along the length of a stem (spiral grain and diving grain).

Consequently, genetic reductions in the pith-to-cambium gradient of (a)–(d) above would reduce volumetric shrinkage and drying distortion of sawn timber. As biological growth and maturation processes follow logarithmic or exponential curves, the radial wood property gradients (i.e., pith-to-bark — Fig. 1) are greatest in the first growth rings for many conifer species (Donaldson 1995; Persson 1997; Lindström *et al.* 1998; Yamashita *et al.* 2000). This indicates that the largest potential for genetic improvement of drying and structural properties lies in the juvenile or corewood of the tree, i.e., approx. the first 10 growth rings, which seems to be a valid statement for both fast- and slow-growing conifer species (Fig. 2). Directional shrinkage is a function of microfibril angle and wood shrinkage, and the magnitude of directional shrinkage depends on the cellulose orientation in the cellwall of tracheids (Fig. 3). This means that there will be a nonlinear relationship between longitudinal shrinkage sand microfibril angle in the first growth rings from pith. For instance, a reduction in microfibril angle in the first growth rings from about 40° to 30° should greatly improve the structural and shrinkage properties of wood because a lower microfibril angle in the first growth rings will set a limit for volumetric wood shrinkage and therefore the drying distortion of sawn lumber. The same reasoning seems valid when considering the gradients in spiral grain and diving grain, i.e., the 3-D alignment of tracheids relative to the stem axis (Forsberg 1999; Ormarsson 1999).

In recent years, genetic selection of trees with high modulus of elasticity has been assisted by acoustic assessment of dynamic modulus of elasticity on standing trees (Walker & Nakada 1999; Lindström *et al.* 2002, 2004). These studies reported statistically significant differences in modulus of elasticity of tree clones, indicating possibilities for using clonal forestry as a means to increase the modulus of elasticity of wood. However, from a wood science / tree breeding perspective, complementary measurements with the SilviScan tool (Evans 1999; Evans & Ilic 2001; Evans *et al.* 2001) would be useful to assess how wood property gradients such as tracheid dimensions, microfibril angle, and wood density might differ in tree clones with high modulus of elasticity.

The aim of this study was to determine the range in fibre properties and longitudinal shrinkage gradients in the first growth rings of young *P. radiata* with low and high

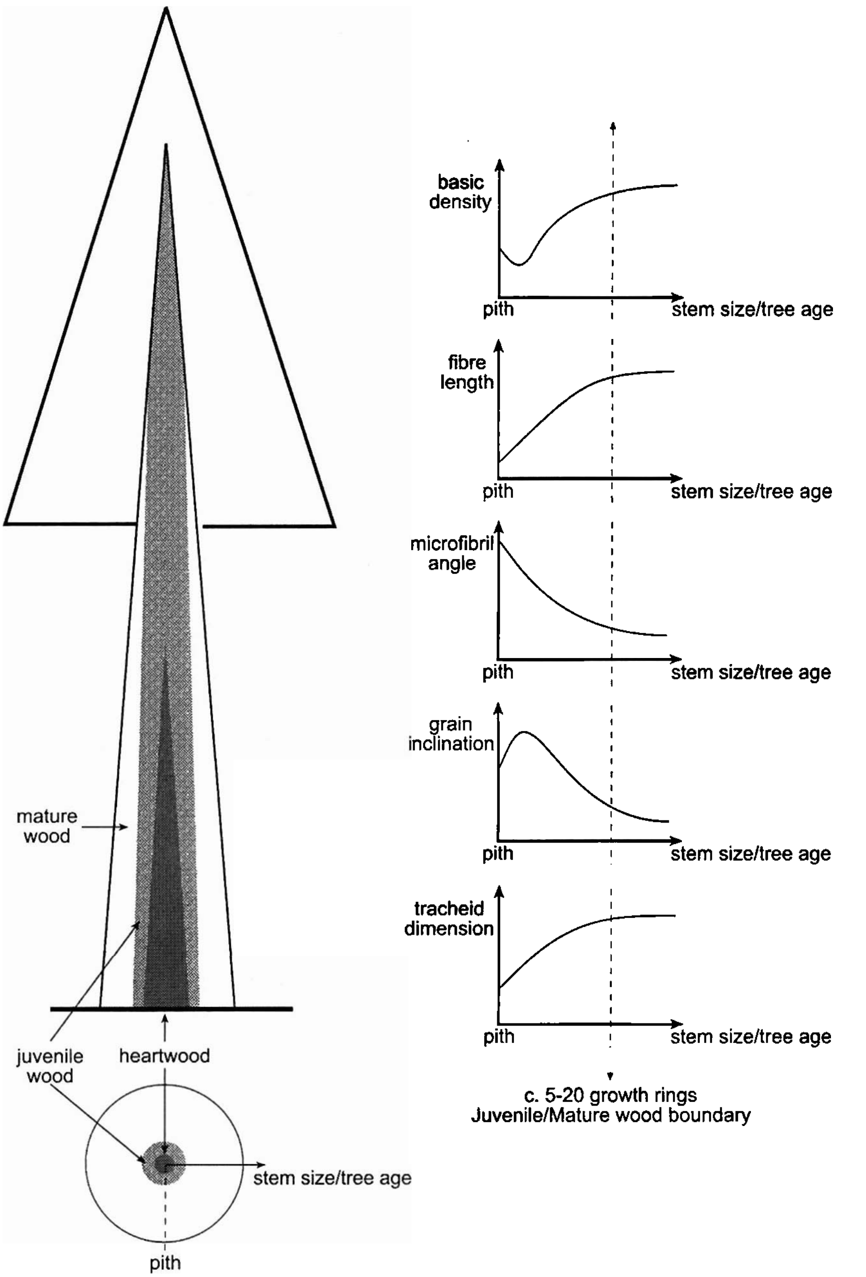


FIG. 1–Typical wood gradients from the pith outwards in a conifer. Wood gradients are most pronounced in the juvenile wood formed in the first 5–20 growth rings from the pith.

modulus of elasticity, and to discuss the likely effect on wood properties of selecting clones with:

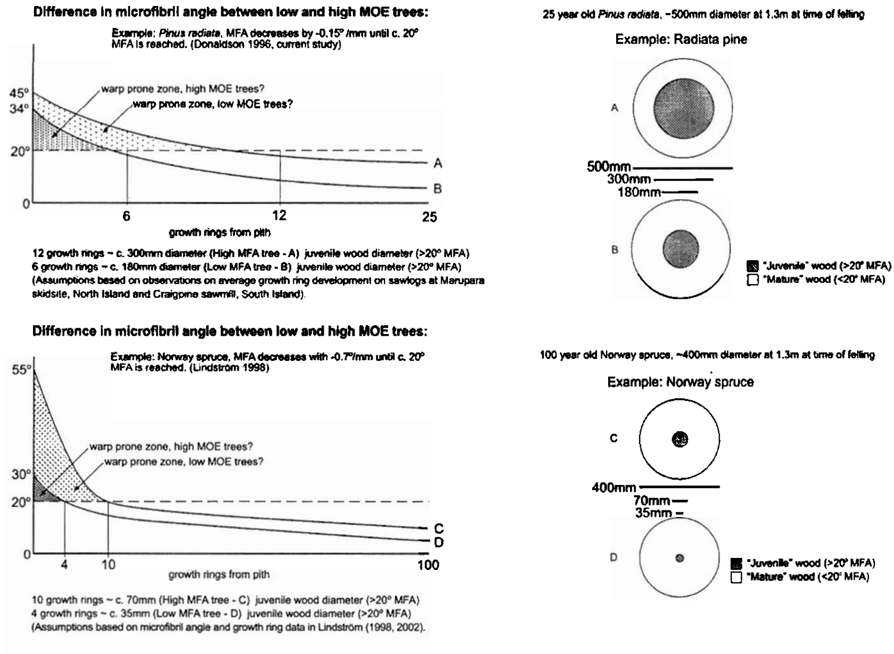


FIG. 2–Microfibril angle gradients from the pith outwards on low and high modulus of elasticity trees. Type B and D trees would be the goal for tree breeding programmes aimed at minimising wood gradients between juvenile and mature wood.

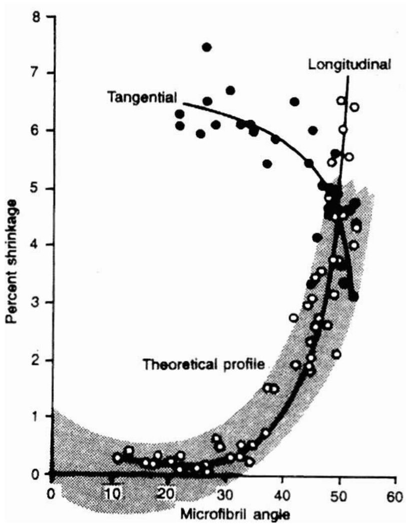


FIG. 3–Influence of microfibril angle on longitudinal shrinkage: experimental data for *Pinus jeffreyii* discs from breast height (*after* Meylan 1968), on which has been superimposed a band of theoretical profiles, depending on the stiffness and shear modulus of the cellulose and hemicelluloses-lignin matrix respectively (*adapted from* Barber & Meylan 1964).

(a) High modulus of elasticity
(b) Low modulus of elasticity
(c) Normal compression wood content
(d) High compression wood content.

MATERIAL AND METHODS

Material

High modulus of elasticity (class (a)) and low modulus of elasticity (class (b)) *P. radiata* clones were selected, based on acoustic transit time measurements in a 3- and a 4-year-old clone trial at Te Teko in the North Island of New Zealand (Fig. 4). Both trials contained approx. 1000 clones with eight ramets per clone. All clones had first been screened (from average stem form and wood density records based on available ramet data for each clone) to ensure that only those with straight stems and generally good growth traits were considered (Fig. 5). High clonal heritabilities for modulus of elasticity, wood density, and microfibril angle were found in an earlier study (*see* Lindström *et al.* 2002 and 2004 for further selection criteria).

The same growth and form traits were used to select two 8-year-old clones (Clones 5 and 10 for category (c)) from a clonal field trial planted at Burnham on the Canterbury Plains (Fig. 4). These trees were grown on a normal plantation regime and were selected to represent young trees with "normal" compression wood content. All trees were pruned to 2.5 m stem height in 1998.

The tree clones grown at Burnham had also been used to establish a compression wood trial near Port Levy on the Banks Peninsula (Fig. 4). The trees in this trial had been staked to a 45° lean and then left to realign themselves (Fig. 6) to see whether there was any difference in compression wood formation between clones (category (d)). All trees in this trial were also pruned to 2.5 m stem height in 1998. Some curved 7-year-old trees representing Clones 2, 5, and 10 were selected to compare any clonal differences in compression wood content.

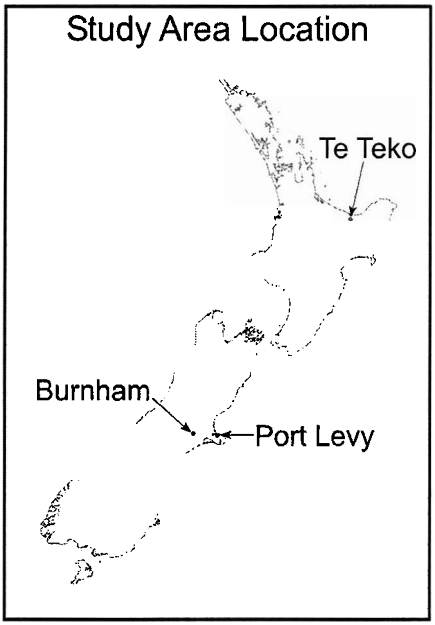


FIG. 4–New Zealand trial locations at Te Teko, Burnside, and Port Levy.

FIG. 5–Three-year-old clone trial at Te Teko, Bay of Plenty. Although the clones in the trial were similar in growth and stem form, they still exhibited large genetic differences in wood properties (Lindström *et al.* 2004)

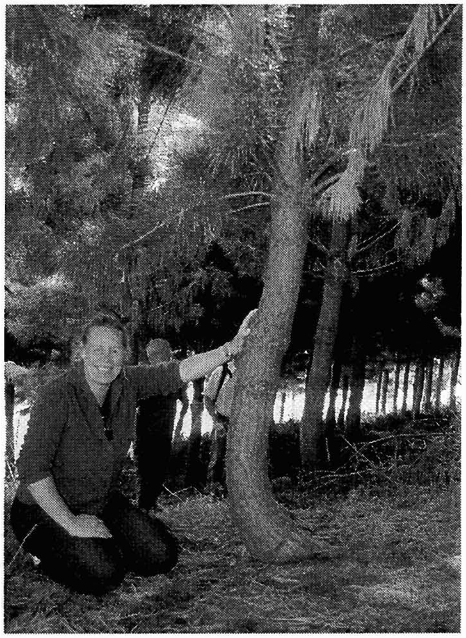


FIG. 6–Compression wood trial at Port Levy, Canterbury. In order to induce formation of severe compression wood, these 7-year-old tree clones were staked to a 45° angle at 18 months of age, then left free to realign themselves.

Four 2 × 7 × 40–100 mm (tangential × longitudinal × radial) profile samples were machined from a stem disc along orthogonal diameters of the (a)–(d) material.

SilviScan-2 (Evans 1999; Evans & Ilic 2001) was used to measure microfibril angle from the cellulose-I 002 azimuthal X-ray diffraction peaks. The standard deviation (S) of the diffraction peaks was used to calculate the microfibril angle according to the following formula (Evans 1999):

$$MFA^2 = 1.64(S^2 - 36) \quad (3)$$

where microfibril angle and S are measured in degrees.

Area-weighted values of microfibril angle were calculated from the pith-to-bark microfibril angle profiles for each clone.

The samples used for microfibril angle measurement were also measured (using Silviscan-2) for conditioned wood density (SSCD), calculated from pith-to-bark profiles integrated over 2.0-mm intervals at 7–8% m.c.

Using the four microfibril angle profiles obtained from each stem disc, linea regression was used to fit the data to a trend line describing the decline in microfibri angle with increasing distance from pith.

Reports by Harris & Meylan (1965), Meylan (1968), Cave (1972), Barret *et al* (1972), and MeGraw *et al.* (1998) did not contain an explicit function that coul calculate the gradient in longitudinal shrinkage, using microfibril angle as an input However, the longitudinal shrinkage data between 20° and 50° MFA given b Meylan (1968) and cited by MeGraw *et al.* (1998) (both studies representative fo longitudinal shrinkage of pine) were used to build a nonlinear model of longitudina shrinkage (Eq. 4)

$$Ls = 0.0049*e^{0.1229x} \quad (4$$

where Ls = Longitudinal shrinkage data and x = microfibril angle data.

Using Eq. (4), the SilviScan-2 pith-to-bark microfibril angle data for material (a and (b) were transferred to longitudinal shrinkage data. A log-linear model wa compared to a linear model by using the Bayesian information criterion (Schwar 1978) that suggested the use of the second model.

Fibre Properties of 3-year-old Clones

Stem discs about 40 mm thick were cut at breast height (1.4 m above ground level from the 3-year-old clones with low and high modulus of elasticity. Discs wer manually cut into wood chips (2–4 mm thick × 40 mm long × 20–40 mm wide) chips for each modulus of elasticity group were pooled, and 200 g of dry chips o each group were placed in separate 3000-ml glass beakers.

A 10% sodium hydroxide (NaOH) solution was added and each beaker was the covered with aluminium foil and placed in a water bath held at +95°C for 4 h. Th beakers were allowed to cool somewhat, then drained and rinsed with water Delignification was continued in the same beakers using two successive treatment of a 1:1 glacial acetic acid (CH_3COOH) / hydrogen peroxide (H_2O_2) solution fo 3 h and 2 h respectively. The delignified fibres were rinsed five times with wate and left soaking for 5 minutes between rinsings.

Pulps from each modulus of elasticity class were placed in a container, diluted wit 15 litres of water, and blended for 2 minutes to break up all fibre lumps. The pul concentrations in the resulting fibre suspensions were determined using T 240-om 93 (Tappi test methods 1994–1995).

In accordance with the standard fibre analysis procedures (T-271, Tappi tes methods 1994–1995), tracheid length, diameter, and fibre coarseness were measure on a 25-ml sample of each pulp suspension using a Kajaani FiberLab™ analyser The measurements were replicated four times (4*25 ml), but only small mean valu differences (<3%) were seen between the four replicated measurements.

RESULTS

Averaged wood properties of the clones sampled from the three locations are given in Table 1.

T-tests of Wood Properties in (a) and (b) Material

According to the PROC T-test analysis (SAS Institute 2002), there were significant differences in microfibril angle and spiral grain between low and high modulus of elasticity clones (Table 2). Although not statistically significant, there was also a tendency for conditioned wood density to be higher and compression wood to be lower in high modulus of elasticity clones. The effect of modulus of elasticity on fibre properties could not be statistically evaluated as the values for each class had been pooled (Table 2). However, the measurements indicate a 10–20% difference in fibre dimensions between the mean values of the clones with low and high modulus of elasticity. Further studies using more clones and/or clone groups would be necessary to evaluate the true effect on fibre dimensions.

The fitted linear regression lines y = 0.3227 – 0.0042x for (a) material, and y = 1,1928 –0.01361x for (b) material, describe the decline in longitudinal shrinkage with increasing distance from the pith (Fig. 7). The hypothesis of identical slope was tested using a t-test procedure (Zar 1999, pp. 360–368) and rejected, with the results giving strong evidence of difference between the two regression lines (t-test value 0.048, critical value at 0.99 confidence interval 2.5780, probability 0.0).

Microfibril Angle and Microfibril Angle Gradients in Trees with Compression Wood

The material selected from the compression wood trial at Port Levy had developmental patterns in microfibril angle that seemed related to the presence of compression wood — i.e., large microfibril angles could be observed in what was visually judged to be compression wood (Fig. 8 and 9). The formation of compression wood seems to create sharp gradients in microfibril angle within the cross-section of a leaning tree. That is, the four scanning directions reveallen larger variation in microfibril variation in trees with much compression wood (Fig. 9 and 10). This means that evaluation of microfibril angle gradients (and therefore longitudinal shrinkage gradients) becomes more or less meaningless for leaning trees because the formation of compression wood is a response to tree lean and the pattern will change over time to form wandering arcs of compression wood within a very short distance of a tree stem (Fig. 8) Moreover, there is a clear site-to-site variability in modulus of elasticity, compression wood, and average microfibril angle as similar clone material was used at Port Levy (leaning trees) and Burnham (non-leaning trees) (Table 1).

TABLE 1–Wood properties of the four tree groups, based on data from three studies (Lindström *et al.* 2002, 2004)

Classification	Tree group: Clone number	Tree group: Tree age	Tree group: Dbh[a] (cm)	Wood and fibre properties: Conditioned[b] wood density (kg/m^3)	Compression[c] wood (%)	Spiral[d] grain (°)	Microfibril[e] angle (°)	Modulus[f] of elasticity (GPa)	Fibre[g] length (mm)	Fibre[h] width (µm)	Fibre[i] coarseness (mg/m)
Low modulus of elasticity	1573	3	8.4	332	22.5*	4.5	38.7	2.25	1.55	34.7	0.180
	832	3	8.8	317	22.2*	4.4	38.4	2.42	1.55	34.7	0.180
	442	3	8.7	355	25.1*	3.4	36.7	2.40	1.55	34.7	0.180
	937	3	11.1	338	15.4*	4.5	37.9	2.52	1.55	34.7	0.180
	1	4	13.5	325	N/A	1.3	36.6	2.61	N/A	N/A	N/A
	2	4	13.0	367	N/A	4.4	38.6	2.7	N/A	N/A	N/A
High modulus of elasticity	846	3	8.4	341	6.0*	2.0	27.7	4.13	1.78	37.5	0.213
	848	3	9.6	356	25.5*	0.8	29.5	4.13	1.78	37.5	0.213
	261	3	8.7	376	19.9*	3.0	28.8	4.37	1.78	37.5	0.213
	644	3	10.2	378	11.2*	2.4	29.8	4.38	1.78	37.5	0.213
	5	4	14.0	336	N/A	3.1	26.7	5.20	N/A	N/A	N/A
	6	4	13.5	368	N/A	4.8	31.8	5.43	N/A	N/A	N/A
	7	4	12.0	349	N/A	3.8	29.5	5.23	N/A	N/A	N/A
High compression wood	10	7	7.7	437	32.6**	N/A	36.5	4.04	N/A	N/A	N/A
	10	7	12.0	319	16.8**	N/A	37.9	2.67	N/A	N/A	N/A
	10	7	8.0	420	14.7**	N/A	40.4	3.58	N/A	N/A	N/A
	10	7	10.9	482	42.3**	N/A	40.6	3.70	N/A	N/A	N/A
	5	7	8.3	406	30.2**	N/A	38.9	3.40	N/A	N/A	N/A
	5	7	11.6	430	43.4**	N/A	33.6	4.80	N/A	N/A	N/A
	5	7	7.7	429	22.4**	N/A	40.7	3.18	N/A	N/A	N/A
	2	7	12.0	522	58.3**	N/A	46.3	2.51	N/A	N/A	N/A

TABLE 1–cont.

Classification	Tree group			Wood and fibre properties							
	Clone number	Tree age	Dbh[a] (cm)	Conditioned[b] wood density (kg/m³)	Compression[c] wood (%)	Spiral[d] grain (°)	Microfibril[e] angle (°)	Modulus[f] of elasticity (GPa)	Fibre[g] length (mm)	Fibre[h] width (μm)	Fibre[i] coarseness (mg/m)
Normal	10	8	12.5	429	14.6**	N/A	34.7	4.61	N/A	N/A	N/A
compression	10	8	12	452	17.3**	N/A	38.9	3.59	N/A	N/A	N/A
wood	10	8	9.2	416	10.1**	N/A	24.7	7.98	N/A	N/A	N/A
	10	8	12.8	429	17.7**	N/A	33.9	4.84	N/A	N/A	N/A
	5	8	13.6	377	24.9**	N/A	29.2	5.49	N/A	N/A	N/A
	5	8	13.2	365	10.8**	N/A	29.2	5.10	N/A	N/A	N/A
	5	8	13	389	15.1**	N/A	28.9	5.71	N/A	N/A	N/A
	5	8	13.8	366	16.9**	N/A	25.8	6.06	N/A	N/A	N/A

* = difference significant at $p \leq 0.01$

** = difference significant at $p \leq 0.001$

[a] Diameter over bark at breast height (1.4 m)

[b] Conditioned wood density (Evans *et al.* 2001) measured at 7–8% m.c. using SilviScan-2

[c] Measured using the image analysis software Metamorph ver. 4.0 and Compression wood analysis ver. 1.0

[d] Average measurement at breast height of south- and north-facing readings (Lindström *et al.* 2002).

[e] Area weighted microfibril angle at breast height measured using SilviScan-2

[f] On 3- to 4-year-old Te Teko clones, swept resonance was used to measure modulus of elasticity at 1.0–1.5 m stem height at 12% m.c. (Lindström *et al.* 2002); on the 7- to 8-year-old clones with high compression wood, the modulus of elasticity at 1.0–1.5 m was calculated using SilviScan-2 (Evans & Ilic 2001)

[g] Average length-weighted fibre length for each modulus of elasticity class

[h] Average fibre width for each modulus of elasticity class

[i] Average fibre coarseness for each modulus of elasticity class

TABLE 2–T test analysis of wood trait differences between the 3-year-old low and high modulus of elasticity groups, using four clones*two replicates for each group.

Wood trait	Average for low modulus of elasticity clones	Average for high modulus of elasticity clones	Difference in mean values, T test
STATMOE[a]	2.4 GPa	4.4 GPa	***
DYNMOE[b]	2.4 GPa	4.3 GPa	***
Microfibril angle[c]	38.0°	29.0°	***
Spiral grain[d]	4.2°	2.0°	**
Conditioned wood density[e]	336 kg/m^3	363 kg/m^3	n.s. ($p = 0.06$)
Compression wood[f]	21%	16%	n.s. ($p = 0.29$)

* = difference significant at $p \leq 0.05$
** = difference significant at $p \leq 0.01$
*** = difference significant at $p \leq 0.001$
a Static loading determination of modulus of elasticity using internodal stem bolts conditioned to 12% m.c. (Lindström *et al.* 2002)
Dynamic determination of modulus of elasticity using swept frequency (WoodSpec™) on internodal stem bolts conditioned to 12% m.c. (Lindström *et al.* 2002)
Area weighted microfibril angle of a stem at 1.3 m, measured using SilviScan-2
Spiral grain close to breast height, measured as the average of south- and north-facing readings on tree stems
Conditioned wood density (Evans *et al.* 2001) measured at 12% moisture content using Silviscan-2
Conditioned wood percentage using the image analysis software Metamorph ver. 4.0 and Compression wood analysis ver. 1.0.

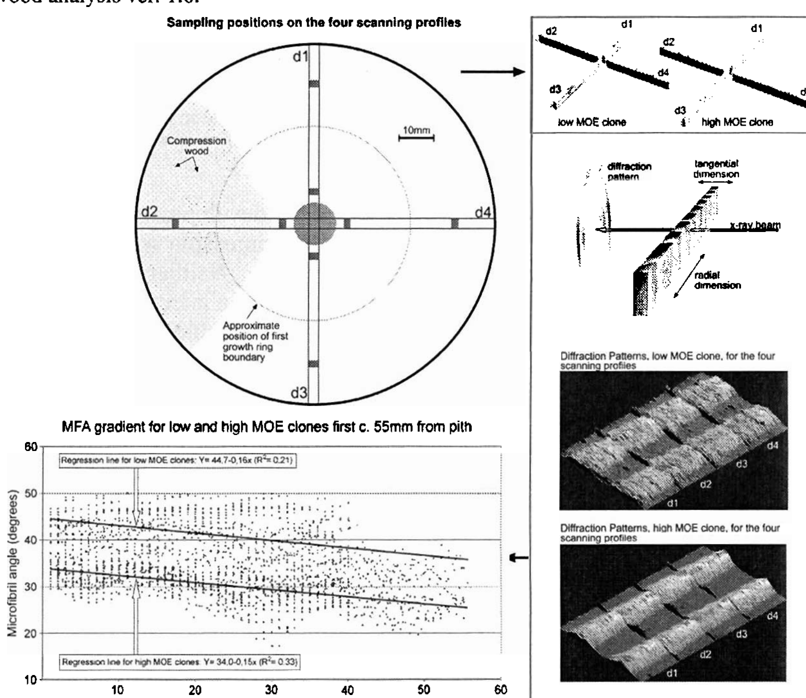
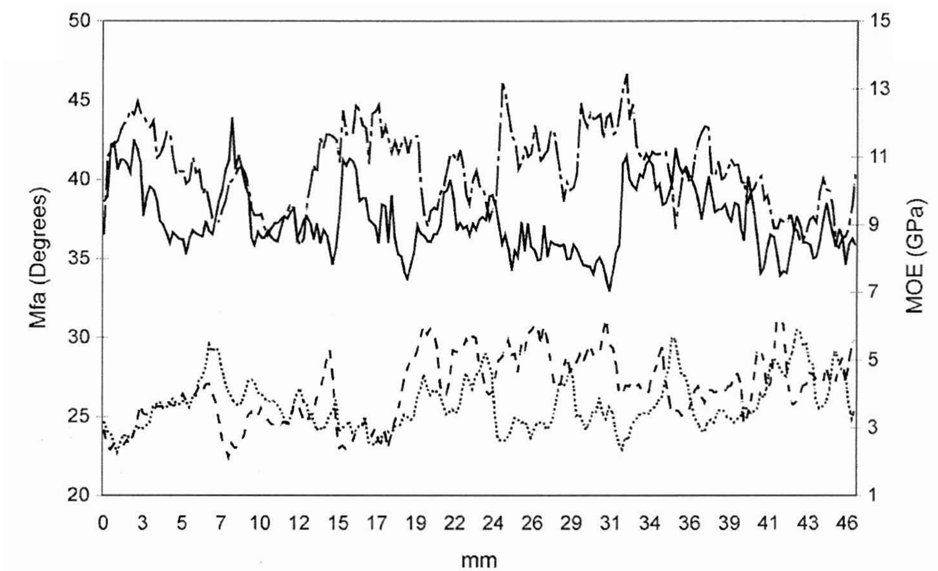


FIG. 7–Scanning directions, diffraction patterns, and examples of microfibril angle gradients for low and high modulus of elasticity clones.



—— Averaged MFA gradient from pith outwards on the non-leaning side (non-compression wood side) calculated based on Silviscan-2 data for 7-year-old clones with high compression wood content.

—- · Averaged MFA gradient from pith outwards on the leaning side (compression wood side) calculated based on Silviscan-2 data for 7-year-old clones with high compression wood content.

– – – Averaged gradient in MoE from pith outwards on the non-leaning side (non-compression wood side) calculated based on Silviscan-2 data for 7-year-old clones with high compression wood content.

------- Averaged gradient in MoE from pith outwards on the leaning side (compression wood side) calculated based on Silviscan-2 data for 7-year-old clones with high compressoin wood content.

FIG. 8–Average microfibril angle and modulus of elasticity development on opposite sides of a leaning stem. Note that the formation of compression wood means a high microfibril angle on the underside of the leaning stem. Neither the leaning nor the non-leaning side seem to display a consistent decline in microfibril angle as trees form arcs of compression wood on both sides of the initial tree lean during the period of re-adjustment (the period thought to display most intense readjustment is boxed). This diagram is an average representation at 1.4 m. Most of the studied trees displayed arcs of very severe compression wood (with very high microfibril angle) and these arcs shifted during the period of re-adjustment (Fig.9) giving sudden peaks in microfibril angle.

Dependence of Modulus of Elasticity on Measured Wood Properties

The effect of wood properties on static and dynamic modulus of elasticity of the 3-year-old clone material was evaluated using PROC REG in the statistical software SAS ver. 8.0 (SAS Institute 2002). Microfibril angle was largely responsible for differences in modulus of elasticity, although some of the other measured wood

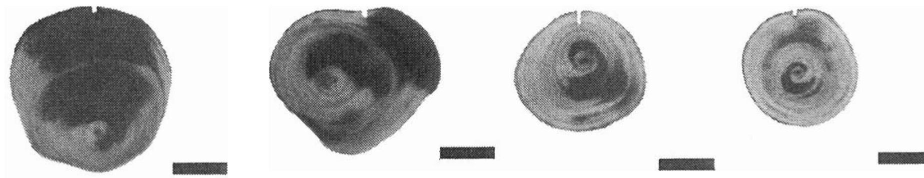


FIG. 9–Compression wood formation wanders as a result of over-compensation where the tree starts to form compression wood on what was originally the upper side of the leaning stem. This phenomenon is apparent in these stem sections of the same tree at 0.2, 0.5, 0.9, and 1.4 m. The notch on each section indicates the southern exposure of the tree. Within 1.2 m, the position of compression wood differs substantially and the shifting arcs produce a microfibril angle development that is not a gradually declining gradient because it arises from the tree's attempt to readjust in order to achieve a straighter stem.

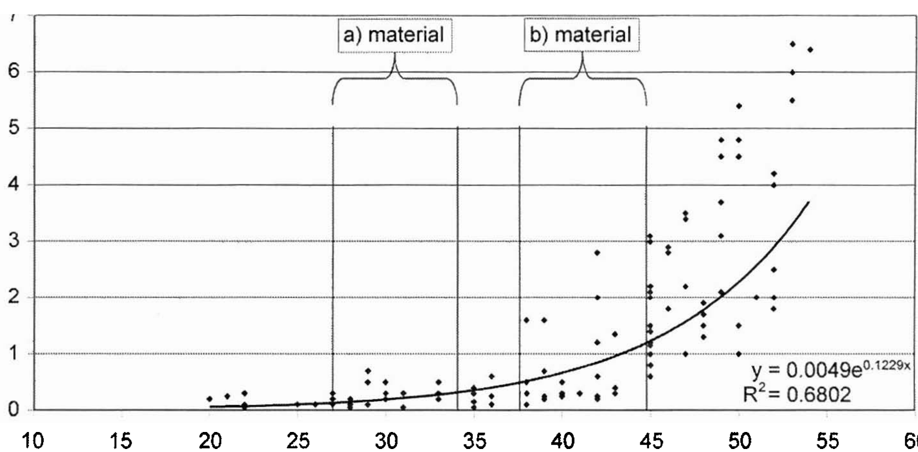


FIG. 10–Range in microfibril angle of the (a) and (b) material in comparison to the longitudinal shrinkage gradient, based on data of Meylan (1968) and MeGraw *et al.* (1998). Selection of high modulus of elasticity clones (the (a) material) will yield smaller shrinkage gradients than in low modulus of elasticity clones (the (b) material). The actual microfibril angle data were fitted with a logistic timeseries function and the resulting slope gradients for the (a) and (b) material were found to be statistically different.

properties (spiral grain, conditioned wood density) were also found to be correlated with modulus of elasticity (Table 3).

DISCUSSION

Active selection of trees with desired growth traits, i.e., tree form, branching, and stem volume, has provided the basis for tree breeding programmes, although some consideration has been given to wood properties (Burdon & Low 1992; Sorensson

TABLE 3–The dependence of modulus of elasticity on wood characters, for the 3-year-old low and high modulus of elasticity clones, using four clones*two replicates for each group.

Regression eq ion	Dependen variable (n	Wood variables in model (n)	Variable(s) used in model, their significance, and their effect on modulus of elasticity (negative or positive)			R^2Adj	RMSE (GPa)
	Static modulus of elasticity (n= 16)	1	Microfibril angle	***	–	0.86	0.38
		1	Spiral grain	**	–	0.42	0.70
		1	Conditioned wood density	**	+	0.33	0.83
		1	Compression wood	n.s.	–	0.10	0.93
		2	Microfibril angle	***	–		
$Y = \sum_{i=0}^{n} b_i x_i + \varepsilon_i$			Conditioned wood density	*	+	0.89	0.34
	Dynamic modulus of elasticity (n= 16)	1	Microfibril angle	***	–	0.87	0.38
		1	Spiral grain	**	–	0.45	0.68
		1	Conditioned wood density	**	+	0.29	0.78
		1	Compression wood	n.s.	–	0.14	0.86
		2	Microfibril angle	***	–		
			Conditioned wood density	*	+	0.89	0.30

* = difference significant at $p \leq 0.05$
** = difference significant at $p \leq 0.01$
*** = difference significant at $p \leq 0.001$

et al. 1997; Jayawickrama & Carson 2000; Burdon *et al.* 2004; Kumar 2004). The main objective of tree breeding programmes essentially remains the creation of healthy, vigorous, fast-growing trees which will reach commercial maturity at a younger age, bringing a huge advantage to the forest sector. However, fast tree growth paired with lower age at clearfelling will also mean that the sawlogs produced will contain an increasing proportion of juvenile wood with poor structural and drying properties. This is further aggravated in that consideration of "wood quality" traits in breeding programmes has been hampered by slow determination of stem wood properties. As a result, attempts to include "wood quality" as a selection trait have often been either neglected or restricted to wood density, which sometimes could be counter-productive considering the linkage between wood density and compression wood content. Any selection of trees for high wood density has to be accompanied by a rather complex screening for compression wood of the sampled wood (cores) otherwise there may be an indirect selection of trees with higher compression wood content.

Recently, there has been promising development in non-destructive or semi-destructive evaluation of wood quality. One non-destructive evaluation method, based on acoustic technology, can be used to measure modulus of elasticity of wood fast and accurately, and has consequently been used in practical assessment of wood quality in tree breeding trials and clonal trials (Huang *et al.* 2003; C.T.Sorensson pers. comm.). For instance, the results of two earlier studies (Lindström *et al.* 2002, 2004) indicated more than two-fold differences in clone modulus of elasticity, showing considerable potential for improvement in juvenile wood by using clones with superior modulus of elasticity.

The modulus of elasticity of wood reflects the underlying tracheid and fibre properties, i.e., microfibril angle, tracheid length, tracheid diameter, cell wall thickness, and fibre coarseness (Navi *et al.* 1995; Persson 1997; Ormarsson 1999; Evans & Ilic 2001). These properties regulate wood shrinkage and drying distortion (Barret *et al.* 1972; Forsberg 1999; Persson 1997; Ormarsson 1999) where gradients in microfibril angle and spiral grain are key drivers of drying distortion, while wood density will regulate the absolute wood shrinkage, assuming tracheid diameter is less variable than wall thickness. The main objective of this study was therefore to explore how fibre properties and mechanical properties, commonly used to describe wood quality, might be altered through acoustic selection of trees with high modulus of elasticity in clonal forestry and maybe in the longer term by tree breeding.

Significant differences in microfibril angles were observed between groups of low and high modulus of elasticity clones. More specifically, the high modulus of elasticity clones had an initially lower average microfibril angle than the low modulus of elasticity ones (Table 1 and Fig. 10) . As the gradual decline rate in microfibril angle is similar at about –0.15°/mm for both low and high modulus of elasticity clones, the high stiffness clones might have a microfibril angle of less than 20° by Rings 3–5 while low modulus of elasticity clones do not attain 20° until Rings 10–15 (Fig. 2). Although the decline rate in microfibril angle is similar, these microfibril angle gradients translate into longitudinal shrinkage differences (Cave 1978; MeGraw *et al.* 1998). That is, in low modulus of elasticity clones, the microfibril angle decrease from an average of 45° (close to the pith) to 38° at 60 mm will mean a substantial longitudinal shrinkage difference over the same distance. In the high modulus of elasticity clones, if the average microfibril angle is 34° at the pith decreasing to 27° at 60 mm from the pith, theoretically the lengthwise shrinkage will be smaller (Fig. 11). When Eq. 4 is used to calculate the longitudinal shrinkage from the actual microfibril angle data to derive fitted shrinkage gradients (Fig. 7) these differences become apparent. Assuming there are no other wood defects, the uneven longitudinal shrinkage would only create bow distortion in a sawn board. In practice, there is huge individual variation in spiral grain and diving grain of growth rings in a tree often caused by a non-central or meandering pith position, and such grain differences will interact with a high longitudinal shrinkage gradient. Logs are obviously not perfect cylinders; they vary in geometrical shape according to growth conditions such as tree lean or uneven crown competition. Therefore, the shrinkage pattern of a cut piece of lumber is not a direct function of the average distance from the pith as the somewhat random pith position in a saw log creates an unequal shrinkage response on different sides of a concentric stem section. High longitudinal shrinkage given by

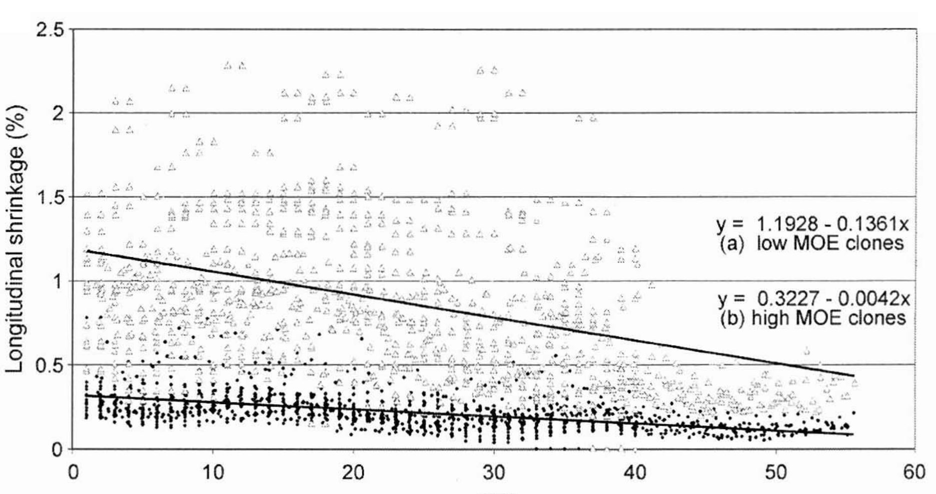


FIG. 11–Longitudinal shrinkage gradients for low and high modulus of elasticity clones fitted with loglinear regression.

high microfibril angle will interact with spiral grain to produce excessive twist distortion. Hence, the magnitude and direction of drying distortion will be a complex function of the combination of spiral grain, microfibril angle gradients, and relative position from the pith (Forsberg 1999).

Uneven crown competition, strong wind exposure, tree lean, or uneven branching could further aggravate the dimensional stability of wood in trees grown under such conditions. The trial in Port Levy provided an example of the effect of extreme growth conditions in trees staked to 45° then left to re-align themselves into a more upright position. The observed pith-to-bark microfibril angle profile of these trees differed on the two sides of the tree stem (Fig. 8 and 9) and no average gradient in microfibril angle should therefore be derived. Nevertheless, the sharp transitions in microfibril angle found between normal and compression wood can be assumed to affect drying distortion of solid wood considerably. There were also indications (although only three clones were used in the study) that different clones subjected to the same 45° staking treatment had differing amounts of visual compression wood accompanied by sudden changes in microfibril angle.

CONCLUSIONS

Tree breeding programmes aimed at selecting trees with better mechanical properties and less drying distortion would ideally be based on a set of easily measured wood properties such as spiral grain and acoustic modulus of elasticity (Sorensson *et al.* 1997; Forsberg 1999; Lindström *et al.* 2002) that reflect the average orientation and ultrastructure of the many millions of tracheids that constitute wood. This study also pointed to the importance of using only visually straight trees when selecting those with high modulus of elasticity. Tree lean will have a marked effect on wood structure development, i.e., wood density and microfibril angle, and therefore influence both modulus of elasticity and longitudinal shrinkage gradients. A second priority would be to assess less easily measured traits such as compression wood content and lignin composition that could provide additional data for selection of trees with better wood properties.

In the current study, it seemed that selection for high modulus of elasticity clones could result in a compounded indirect selection for lower microfibril angle, lower spiral grain, and higher wood density, possibly with somewhat larger tracheid dimensions (Tables 1 and 3). In other words, it seems that young trees from clones with high modulus of elasticity have lower initial microfibril angle and slightly larger tracheid dimensions than low modulus of elasticity clones (Fig. 7 and 11). It seems likely that selection of clones with high modulus of elasticity will yield indirect improvement in form stability and wood shrinkage as the shrinkage gradients are less severe in high modulus of elasticity trees. The use of clonal forestry could blur the gradual transition boundary between juvenile and mature wood in sawlogs cut from genetically improved trees, thereby reducing the drying distortion of sawn lumber.

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