# Modelling within-tree and between-tree variation in Douglas-fir wood and lumber properties

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NZ Douglas-fir Cooperative

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# MODELLING WITHIN-TREE AND BETWEEN-TREE VARIATION IN DOUGLAS-FIR WOOD AND LUMBER PROPERTIES

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## Abstract

The ability to accurately predict tree growth and wood quality is becoming increasingly important, as forest management focuses more closely on end-use. This project focuses on a detailed examination of the wood and lumber properties of eighteen trees in a stand aged 41 years, grown at Rotoehu Forest from seed originating from Fort Bragg (coastal California). The eighteen trees were selected from 49 trees for intensive study using a 'response surface' sampling design to cover the range for density, microfibril angle (MFA) and branch size, and thus for stiffness (MoE). A range of wood properties including MoE, strength (MoR), density and MFA were assessed from cores, discs, small clears extracted from short billets and timber recovered from sawlogs. These tests were designed to cover the radial and vertical distributions within the trees. All properties improved with increasing distance from the pith. Density showed much less of a radial trend than MFA with MoE being intermediate. All properties showed only a small effect of improving quality with height. Between tree variation was high for density and MoE, but relatively low for MFA. A model were constructed to predict timber MoE from the breast height properties of outerwood density and branch index, which explained 64% of the whole tree timber MoE.

## Introduction

This project is the first stage in a series aimed at constructing a new generation of predictive models of Douglas-fir wood quality in New Zealand. It focuses on a detailed examination of the wood and lumber properties of eighteen trees in a stand aged 41 years, grown at Rotoehu Forest from seed originating from Fort Bragg (coastal California). The eighteen trees were selected from 49 trees for intensive study using a 'response surface' sampling design to cover the range for density, microfibril angle (MFA) and branch size, and thus for stiffness (MoE).

Three sawlogs measuring 4.8m in length were recovered from each tree and sawn to 90*45mm timber. In addition, standard small clears measuring 20mm*20mm* 300mm were recovered from billets located between the sawlogs, and at both ends of the tree. Stiffness (MoE) and strength (MoR) were measured on both the small clears, and the sawn timber, and related to non-destructive measurements made at breast height for density using 5-mm increment cores, and for density, MFA, and predicted MoE using 10mm cores analysed by SilviScan2. SilviScan2 analysis was also used to characterise wood properties from 50mm discs removed adjacent to the billets and sawlogs. In addition, measurements of sound velocity were made on one-metre lengths of the standing trees at breast height.

In the study reported here, emphasis has been placed on defining the within-tree and between-tree variation in the key wood and lumber properties of density, MFA, MoE and MoR, based on data from the disks, billets (small clears) and sawlogs (sawn timber). Furthermore, it has been attempted to model these from non-destructive sampling of the trees at breast height.

## Background

The ability to accurately predict tree growth and wood quality is becoming increasingly important, as forest management focuses more closely on end-use. Assessing and predicting the yield and quality of the wood resource at the forest level plays a key role, and enables forest managers to supply a well-specified range of wood products, rather than a random batch of stems. This increases the possibilities for targeting production towards certain end-products, and thereby attain better prices. Furthermore, it will assist breeders in eventually improving product quality and yield.

Based on forest stand information (e.g. growth conditions, silviculture, etc.) and using mathematical models it is possible to predict tree growth. Similarly, the distribution to quality grades may be generated from knowledge about the trees harvested. Existing models for Douglas-fir in STANDPAK predict timber visual and stress grades using a regression approach to link measured stand parameters (Branch Index (BIX), wood density, small-end diameter (SED)) to timber grade. However, the prediction error is large, possibly because at least one key wood property - microfibril angle (MFA) - is missing.

### *Tree breeding*

Choosing the “right” traits to select for in breeding programmes is a key to maximising the economic gains of breeding programmes. All the main components of profitability in lumber production should be included in the breeding objective and the related selection criteria, i.e. the physical properties that can be measured or evaluated in progeny tests of immature trees. Existing breeding programmes for Douglas-fir in NZ have targeted improvement of volume growth and tree form. Stiffness (MoE) of structural timber is another important component, and needs to be included in future breeding objectives.

Measurements from provenance trials, planted in 1959, have shown that, on average, coastal Californian provenances produce 22% more over-bark stem volume than the ‘Kaingaroa’ ex Washington control seedlot. An earlier study of wood density variation in these provenance trials (Lausberg *et al.* 1995) showed only a small amount of variation in breast height outerwood density between provenances (±3%) and very large within-provenance variation (±14%). Therefore this study has been based on one of the highly productive coastal Californian provenances, from Jackson State Forest at Fort Bragg.

### *Density and microfibril angle in small clear samples*

Many researchers have found that wood density (specific gravity) is one of the prime determinants of wood stiffness and strength (Bamber and Burley, 1983; Megraw, 1985; Zobel and Buijtenen, 1989; Björklund and Walfridsson, 1993; Mamdy *et al*., 1999). Density alone may explain up to 60-70% of the variation in modulus of elasticity (MoE) in clear wood (Rozenberg *et al*., 1999; Evans and Ilic, 2001).

There is also plenty of evidence in the literature that stiffness and strength properties of small clear wood samples are partly dependent on microfibril angle (Mark and Gillis, 1973; Bendtsen and Seft, 1984; Megraw, 1985; Cave and Walker, 1994; Donaldson, 1995; Butterfield, 1997; Cown *et al*., 1999; Evans and Ilic, 2001). Alone MFA may explain up to 60-70% of the variation in MoE. Furthermore, MFA is also a useful surrogate for longitudinal shrinkage (distortion), depending on how the saw pattern intercepts the MFA profile (Zobel and Buijtenen, 1989; Butterfield, 1997) and MFA also provides valuable information to the pulping industry (Megraw, 1985).

Evans and Ilic (2001) found that density and MFA together explained up to 94 % of the variation in MoE in small clear samples from *Eucalyptus delegatensis*. Similar investigations (Evans, unpublished) for other species found the same strong relationship, which appears to be generic (i.e. independent of species). Thus, by modelling MFA and density most of the variation in strength properties for the clear wood is captured, and reasonable predictions of MoE can be made.

The within-stem variation in density is well described for several of the key tree species in the world (Cown and McConchie 1982; Zobel and Buijtenen, 1989; Leban and Duchanois, 1990; Lindström, 1996). Similarly, Megraw *et al*. (1999) found that the variations in microfibril angle within loblolly pine stems followed characteristic patterns. Thus, together with several other investigations (Butterfield, 1997; Herman *et al*., 1999; Evans *et al*., 2000) there is good evidence that it is possible to make reasonably accurate models of within-stem variation in density and MFA for several tree species. From these models it may be possible to predict MoE for the 'wood between the branches' with confidence.

***Modelling with-tree and between-tree variation in wood properties***

Modelling the within- and between-tree variation in radiata pine wood properties was done by Harris (1965). Later the idea was investigated and redeveloped for Scots pine in Finland (Väisänen *et al*. 1989), Norway spruce in France (Leban and Duchanois, 1990), and applied to a stand-alone model for radiata pine in New Zealand (Tian *et al*., 1995).

Building similar models for Douglas-fir should enable prediction of density and MFA based on sample measurements of outerwood at breast height. Hence, given this information it may be possible, based on the generic relationship between density/MFA and MoE for small clear samples (Evans and Ilic, 2001), to predict the MoE of clearwood of Douglas-fir. This information may then be used as input into a strength prediction model that takes into account the effect of knots. A mechanistic approach has been successfully developed by Cramer and McDonald (1989). This approach should be superior to the current empirical regression-type approach used in STANDPAK e.g. Whiteside *et al*. (1987).

In essence, the entire suite of models makes up what may be termed a "*virtual stress grader*". This will make it possible to predict the MoE of joists, given easily measurable stand information. Furthermore, it may be possible to evaluate the stiffness of virtual logs sawn by AUTOSAW (Todoroki, 1990). By varying the sawing pattern and the details of the virtual logs, a set of typical stress grade distributions for different combinations of sawing pattern and stand condition may be calculated. The goal is to infer an expected MoE- based sawn timber grade distribution from stand information and sawing pattern, based on "typical distributions" found by iterating the sawing of virtual logs.

## Methods

### *Sample selection*

Compartment 55, Wairoa Road, Rotoehu forest was chosen as the sample stand. The trees are from Forest Research Institute seedlot 56/654 which was collected by Egon Larsen from Jackson's State Forest, Fort Bragg, California in 1956. This seedlot is represented in the series of provenance trials planted in New Zealand in 1959, and is one of the highest-yielding of the coastal Californian fog-belt provenances in these trials (Knowles and Kimberley, 2002), showing a 34% gain in volume MAI compared to the control seedlot collected in Kaingaroa Forest, of Washington origin. Compartment 55 was planted in 1961, and was thus 41 years old in 2002. Initially, 49 trees, spanning the diameter range, were sampled by a single breast-height pith-to-bark 12mm core which was analysed by SilviScan for outerwood density and MFA, and then 18 study trees were selected across the available diameter/wood density/MFA matrix. A response surface sampling design was followed (Box, 1954) in an attempt to improve statistical efficiencies.

The within- and between-tree variation of the 18 study trees was investigated by extracting small clear samples and wood discs from each tree. Five 40 cm-long billets and five 5-cm discs were cut from each tree at intervals along the stem, between which three standard sawlogs measuring 4.8m in length were recovered. The vertical sampling for the small clear samples and the SilviScan single radial strips was immediately adjacent, and closely intercalated with the sawlogs. This allowed the MFA, density, MoE and MoR values to be related for each disk, billet, and sawlog position.

### *Small Clears Testing*

Sets of standard small clear samples (20x20x300 mm finished size) were extracted from the billets at approximately ten growth-ring intervals from the pith, along two opposite radii, i.e. two to six small clear samples from each billet, depending on billet age. A total of 500 small clears were cut from the eighteen trees. Density, static and dynamic MoE were determined from the small clear samples. Samples were air-dried to equilibrium moisture content, and actual MoE values for each sample were then adjusted to 12% emc and the variance among opposite radius samples within trees was estimated relative to other sources of variation.

Wood basic density and static MoE from small clears was measured y standard methods of BS 373:1957(1986), *Methods of Testing Small Clear Specimens of Timber*, at Forest Research, Rotorua. Testing was carried out on an Instron universal testing machine having a Grade 1 verification certificate under International Standard ES ISO 7500-1 1999. Dynamic MoE of the small clears was assessed by measuring sound velocity using the PUNDIT system.
Dynamic MoE was also measured on a sub-set of 200 small clears at CSIRO, Melbourne, using a resonance method described by Ilic, 2002.

### SilviScan *testing*

The radial changes in density and MFA were measured at six height positions using *SilviScan-2* (Evans and Ilic 2001) at CSIRO, Melbourne. In addition to the initial breast height cores, pith-to-bark strips from the disks were cut as 15x15 mm, green size. These had all traces of bark removed, and were soaked in a 96% ethanol solution for a total of six days replacing the ethanol every two days. On arrival at CSIRO Melbourne, the strips were re-machined to a final size of 7 x 2 mm. Each radial strip was then scanned using X-ray diffraction and X-ray densitometry, to provide estimates of each ring's MFA and density respectively. Predictions of individual ring MoE at each height position of each tree were derived from these data.

***Gravimetric measurement of density***

An important component of the study was the provision of data sets describing density and MoE from alternative methods, enabling ready conversion from one method to another. Density measurement at Forest Research has traditionally been done using standard gravimetric methods. All five disks per tree were sampled for basic wood density, with the sampling point centred on the 10 ring positions. Two opposing bark-to-bark wedges were analysed from each disk.

***Breast height reference***

In modelling wood properties, particularly for forest sampling and tree improvement programmes, it is necessary to have a reference point for the developed relationships, preferably of a non-destructive nature. A convenient reference is usually breast height outerwood, sampled by increment core. This reference point was obtained in this study by extracting two 5mm outerwood cores (50 mm in length) at breast height, which were analysed for density, and one 10mm pith-to-bark core, also taken at breast height, which was analysed using SilviScan-2 for density, and for MFA. From these results, it is possible to obtain a prediction of MoE, termed SilviScan-2 MoE (SS2 MoE). In addition, measurements of sound velocity on a one-metre vertical section of the stem, centred on breast height (1.4m) were also recorded using an IML electronic hammer. Two readings on opposite sides of the tree were recorded, and averaged to obtain what is termed "sound velocity".

***Branch measurements***

Before felling, quartiles (N, S, E and W) were marked on the bark at the base of the tree. Following felling, logs were numbered on the exposed butt section, and marked from base to top, showing location of quartiles, disks, billets, and logs. All branches were measured in 1cm diameter classes, by quartile, in the perpendicular plane relative to the standing tree. This enabled the derivation of standard branch indices, including BIX, which is the mean of the largest four branches per sawlog, contributed as one branch per quartile. Branch condition (dead/alive) was also recorded, along with the height of the lowest green branch, and lowest green whorl. Logs were recovered down to approximately 250mm SED.

***Log preparation***

All logs were cut to 4.8m length. Each log was numbered with a tag stapled to the small end, and with paint. All logs were measured across the minimum diameter, and again at right angles to that, at both the small and large end. A standard 3D volume formula was applied (Ellis, 1982) to derive volumes. At the end of log-making, each log had concentric growth rings spray-painted as follows as a guide to sawn-timber-position in log and cambial age at the time of wood formation.

Colour codes for concentric ring painting of log ends (both log ends so marked):

| | | |
|---|---|---|
| Rings 0 to 9 | (mean age 5) | blue |
| Rings 10 to 19 | (mean age 15) | red |
| Rings 20 to 29 | (mean age 25) | green |
| Rings 30 + | (mean age 35+) | yellow |

*Sawn timber recovery*

All 54 sawlogs were sawn to maximise recovery of timber of nominal 100mm*50mm size. Sawing took place at the Waiariki Polytechnic Timber Industry Training Centre sawmill at Rotorua. The cant was centred on the pith using a "split-taper" alignment to attempt to saw parallel to the pith, as far as possible. Initial flitches of 50mm thickness were recovered, followed by a central cant (or two, depending on log diameter) of 100mm thickness, which was then flat resawn to recover timber of 50mm thickness * 100 depth. Timber sizes smaller than 100*50mm were not recovered. The timber was then kiln dried to 12% moisture content over four days, using the following simplified schedule (based on Kininmonth & Williams 1974;
Dry Bulb 75 deg C Wet Bulb 65 deg C.
Target average MC 10 - 12% approx (sapwood boards <15% mc)
Final steam conditioning @ 100/100 deg C for 4 hours

The timber was then gauged to 90*45mm final size.

*Sawn timber testing of MoE and MoR*

The dry, gauged timber was tested for long-span modulus of elasticity as a joist, LmoEj, in the Baldwin universal test machine, replicating the action of the E-grader. The span was typically 0.3m shorter than the piece length. 141 pieces were measured for their sound velocity using the IML electronic hammer. These pieces were also measured for weight and length.

Using the log number and position-in-log indicator for each length of timber, the timber was sorted in two groups representing 50% each. The intention of the sorting was to ensure an equivalent within-tree position distribution for the two groups.

One group of timber was then tested to destruction to determine the bending strength (MoRj). Figure 2 shows the test arrangement. The total span was 1620mm as recommended in AS/NZS 4063:1992 span of 18:1. Figure 2 shows the test arrangement for the 90x45 timber size.

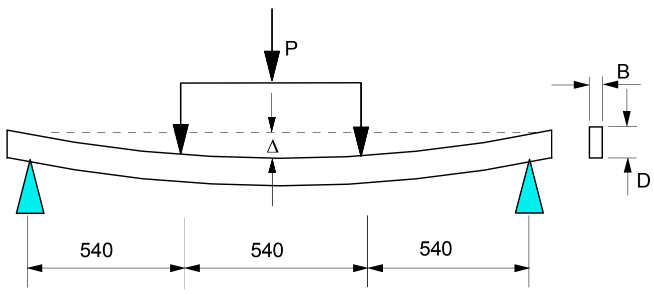


***Figure 2**: Bending strength test configuration*

The Forest Research Grade 1 Baldwin Universal test machine was used for the bending tests. The bending specimens were tested as a joist under monotonic loading and third-point loading as shown in Figure 2. The slope of the linear section of the load/deflection data was recorded along with the maximum load. From the undamaged ends the compression parallel samples were cut.

## Data Analysis

### *Linear model analysis*

Wood properties such as stiffness (MoE), strength (MoR) and density are affected both by patterns of variation within the tree, and differences between trees. The within-tree patterns can be considered to be governed by ring number (or ring age), and height. Linear models were used to determine the percentage variance that can be attributed to within-tree and between-tree effects. In these models, ring number was fitted using linear and quadratic terms, while height was fitted as a class effect with five levels for the small clears and Silviscan data, and three levels for the timber data. The between-tree effect was fitted as an additive class variable with 18 levels corresponding to each of the trees within the study. Interactions between tree and ring and height were also fitted to determine the percentage variance that can be attributed to individual tree variations in the within-tree patterns. With the small clears data, it was also possible to include a 'side' effect to account for differences between two sides of a billet at the same ring number.

### *Nonlinear models analysis*

Although the above linear models were useful for calculating the percentage variance attributable to various components, they were not particularly good for obtaining logical predictions of wood and timber properties. For example, the quadratic terms in these models may predict decreasing stiffness in outer rings. For this reason, nonlinear models were fitted to provide more robust predictions. The following model was found to perform adequately for predicting stiffness, strength, density and MFA:

$$y = a_i(1 + dH)(1 - b\exp(cA))$$

In this model, $y$ is the dependent variable (either MoE, MoR, Density or MFA), $H$ is height (m), and $A$ is age (or rings from pith). The parameters $a_i$, $b$, $c$, and $d$ are estimated using nonlinear regression. A separate local parameter, $a_i$, is fitted for each tree and allows the model to account for differences between trees. The within-tree pattern, which takes account of height and ring number, is controlled by the parameters global $b$, $c$, and $d$. It consists of an exponential term which models the asymptotic behaviour of these wood properties against ring age, and a linear height term. For simplicity, this model does not include any interaction between the within-tree and between-tree components.

### *Tree mean analysis*

As described above, the nonlinear models included parameters, $a_i$, estimated for each tree. These effectively provided predictions for each tree at a height and ring number of zero. For convenience, these were standardised to predict the mean for each tree for ring 20 at breast height (1.4 m). Correlations were calculated among these variables and with branch index, IML sound velocity index and breast height disc density. Regressions were also derived for small clears and timber MoE.

## Results

The percentage variance explained for each term in small clear samples for MoE (18 trees x 5 billet heights x 2-6 small clears/height) was fitted sequentially using linear models, and is given in Table 1. The variation in MoE of all test sticks of all trees was about equally accounted for by a ring (or age) effect, and a tree effect, with sample height having a much smaller effect. Similar results were found for timber MoE, except that the between-tree effect explained a slightly greater proportion of the total variance, probably reflecting the influence on timber stiffness of tree-to-tree differences in branch diameter. About 62% of the variance in timber MoE can be explained by a general within-tree model based on ring number, height and an additive tree term, and a further 10% can be explained as an interaction between tree and ring+height. For SilviScan-predicted MoE (18 trees x 6 heights x 1 radial strip), the within-tree model explained a greater percentage of variance than it did for small clears or timber MoE. Part of the explanation for this is that in the SilviScan data, an equal weighting is given to each ring. In contrast, in the small clear samples the full range of ring positions is not covered, while in the timber data, greater weighting is automatically assigned to the outer rings where the majority of the timber volume resides. The within-tree SilviScan MoE model also predicted a greater height effect (9% of the variance) than the other stiffness samples, although the ring age effect was still dominant (35% of the variance).

The variance explained by the small clears MoR and Density models was similar to the MoE model, but a greater proportion of the variation in MoR, and particularly Density was from the between-tree rather than the within-tree components of the model. Timber MoR was only poorly explained by these models. The model fit for SilviScan density was also poor, reflecting the greater random variation in the small, ring-scale samples assessed by SilviScan, compared with the larger small clears samples. MFA was strongly affected by ring number, and showed very little between-tree variation (4% of total variance). Despite this minimal variation between tree means, there was quite a large interaction effect (14% of total variance), indicating that the relationship between MFA and ring number varied significantly between trees

**Table 1: Percentage variance explained by linear models incorporating ring, height and tree terms fitted sequentially.**

| | Timber | | Small clears | | | SilviScan | | |
|---|---|---|---|---|---|---|---|---|
| Terms | MoE | MoR | MoE | MoR | Den | MoE | Den | MFA |
| ring | 26 | 16 | 31 | 21 | 8 | 35 | 3 | 47 |
| ring+height | 29 | 18 | 36 | 26 | 21 | 44 | 8 | 52 |
| ring+height+tree | 62 | 37 | 61 | 60 | 68 | 57 | 37 | 56 |
| ring+height+tree+int. | 72 | 64 | 78 | 80 | 86 | 71 | 51 | 70 |
| ring+height+tree+int. +side | | | 87 | 87 | 90 | | | |

The percentage variance explained by the nonlinear models is given in Table 2. These models explained very similar levels of variance as the equivalent linear models. A nonlinear model could not be successfully fitted for timber MoR.

**Table 2: Percentage variance explained by nonlinear models incorporating ring, height and tree terms fitted sequentially.**

| | Timber | | Small clears | | | Silviscan | | |
|---|---|---|---|---|---|---|---|---|
| Terms | MoE | MoR | MoE | MoR | Den | MoE | Den | MFA |
| ring | 26 | - | 31 | 21 | 9 | 40 | 2 | 57 |
| ring+height | 27 | - | 35 | 24 | 16 | 47 | 5 | 58 |
| ring+height+tree | 62 | - | 60 | 59 | 64 | 61 | 35 | 63 |

Figs 1 to 7 show model predictions of each property against ring number for a range of heights for the 'mean' tree, and for the best and worst trees in the sample at 5 m height. Because the models contain no interaction terms, the predictions for the best and worst tree are 'parallel' to the mean tree. In practice, this is an oversimplification as individual trees show some variation in slope against ring number.

Small clears MoE averaged about 20% below timber MoE, despite the latter including the effect of branches. This anomaly has not yet been fully explained but is presumably due to a scaling effect. Obviously timber stiffness is the more important variable in relation to value. SilviScan-predicted MoE averaged the same as timber MoE.

Apart from this overall difference between the small clears and timber MoEs, the within-tree models for the three MoE variables are quite similar and are dominated by ring number with a much smaller height effect. However, in general the SilviScan model shows a greater ring and height effect than the small clears model. The timber model shows a less rapid approach to the asymptote than the other models, which approach maximum MoE by ring 15. This is possibly a sampling artifact caused by the slightly less exact ring positions of timber pieces compared the other sampling methods. The height effect is noticeably less pronounced for the timber samples. Perhaps the effect of increasing of clear wood stiffness with height is countered by the larger branch diameters in upper logs.

SilviScan (air-dry) density is consistently over-predicted compared with standard measures of basic density, but apart from this, the general patterns of variation in density against ring age and height are very similar (Figs. 5 and 6).

There is an extremely pronounced decreasing trend in MFA (Fig. 7) with ring number rapidly approaching an asymptote by ring 10, with minimal height or between-tree effects.

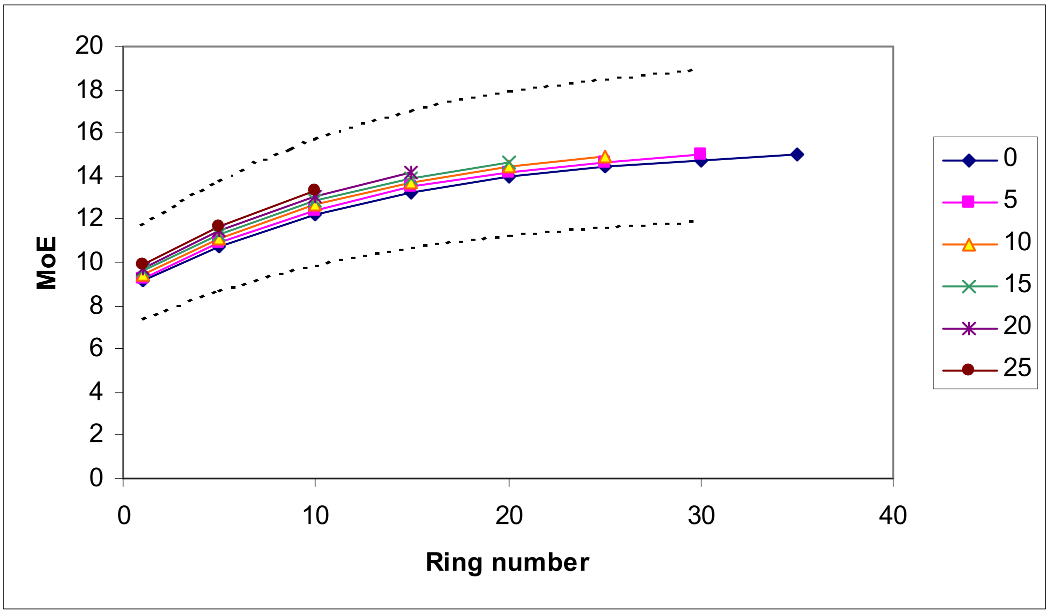


**Fig. 1: Timber MoE versus ring number and height (m) for the mean tree. The dashed lines show the MoE of the best and worst trees (tree numbers 50 and 3 respectively) at 5 m height.**

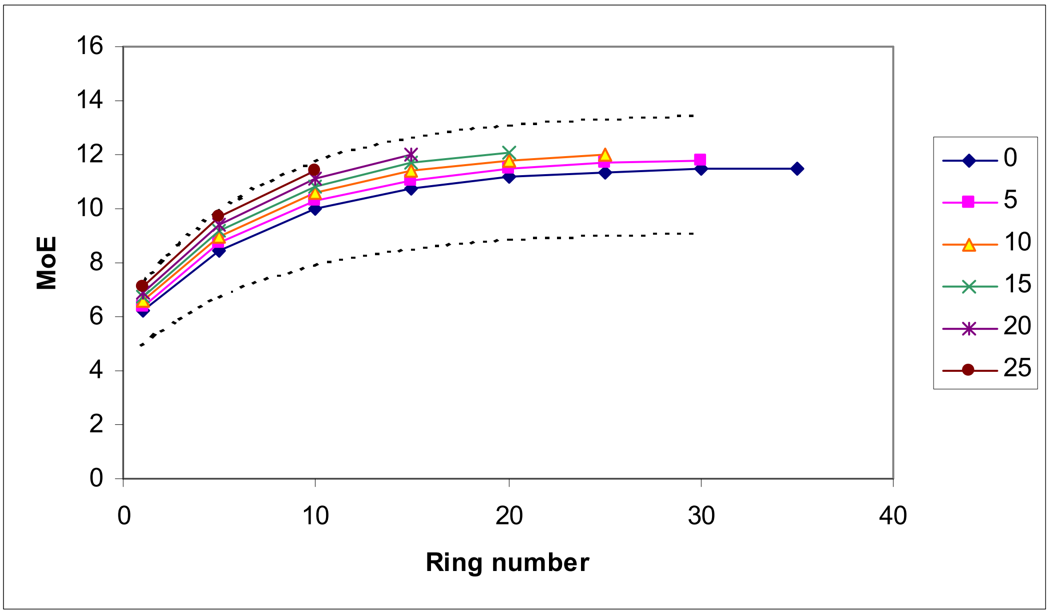


**Fig. 2: Small clears MoE versus ring number and height (m) for the mean tree. The dashed lines show the MoE of the best and worst trees (tree numbers 50 and 3 respectively) at 5 m height.**

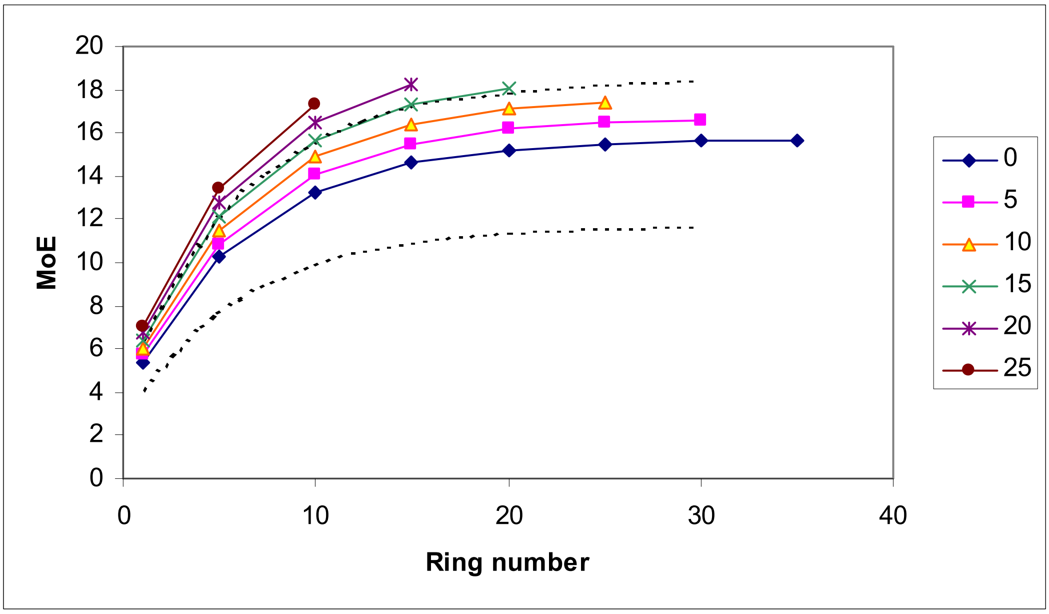


**Fig. 3: Silviscan MoE versus ring number and height (m) for the mean tree. The dashed lines show the MoE of the best and worst trees (tree numbers 50 and 3 respectively) at 5 m height.**

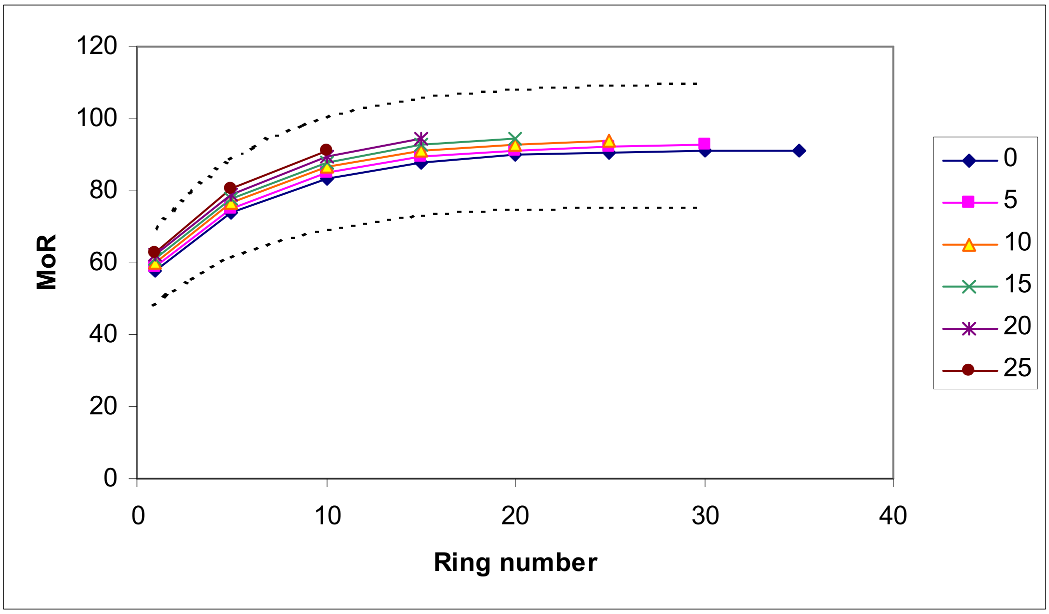


**Fig. 4: Small clears MoR versus ring number and height (m) for the mean tree. The dashed lines show the MoR of the best and worst trees (tree numbers 50 and 3 respectively) at 5 m height.**

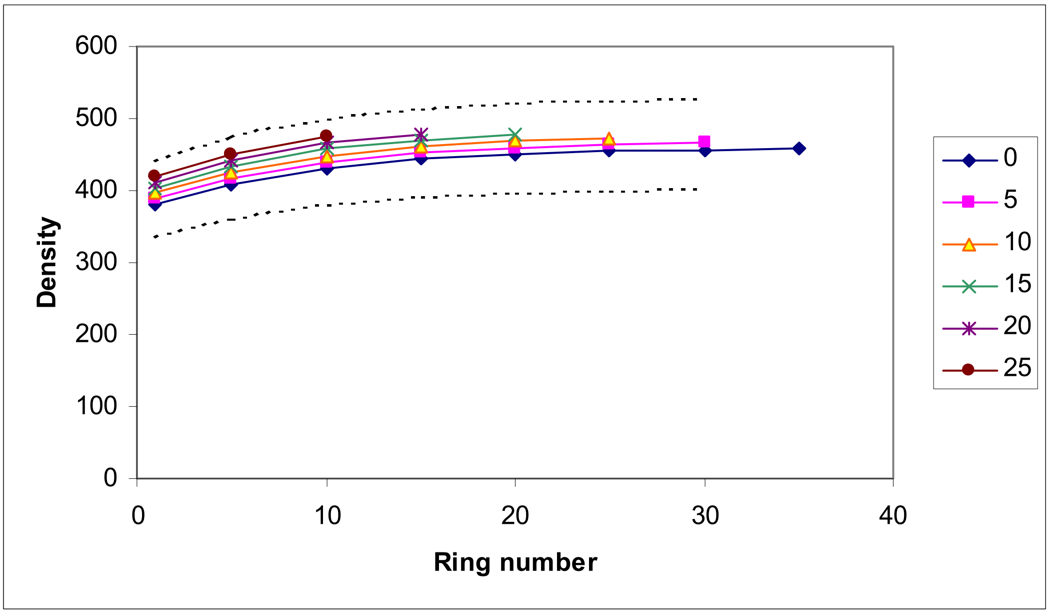


**Fig. 5: Small clears density versus ring number and height (m) for the mean tree. The dashed lines show the highest and lowest density trees (tree numbers 50 and 3 respectively) at 5 m height.**

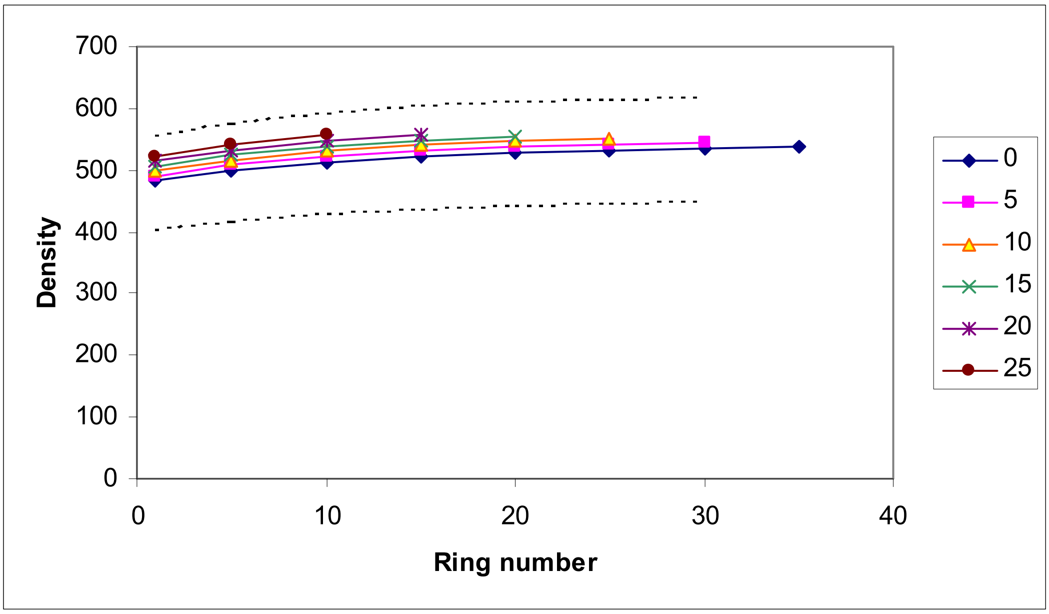


**Fig. 6: Silviscan density versus ring number and height (m) for the mean tree. The dashed lines show the highest and lowest density trees (tree numbers 50 and 3 respectively) at 5 m height.**

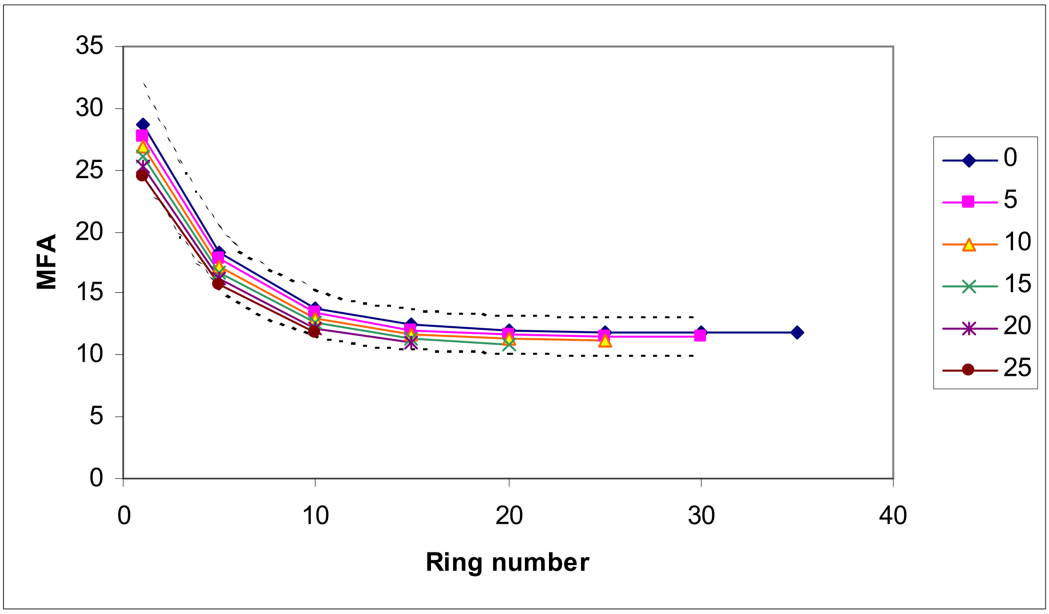


**Fig. 7: Silviscan MFA versus ring number and height (m) for the mean tree. The dashed lines show the highest and lowest MFA trees (tree numbers 40 and 27 respectively) at 5 m height.**

The distributions of timber MoE from the best and worst trees in the study (Fig. 8) demonstrate the extent of the tree-to-tree variation. Within-tree variation is demonstrated by the distributions of MoE in timber centered within the inner 7 rings contrasted against timber from beyond ring 20 (Fig. 9).

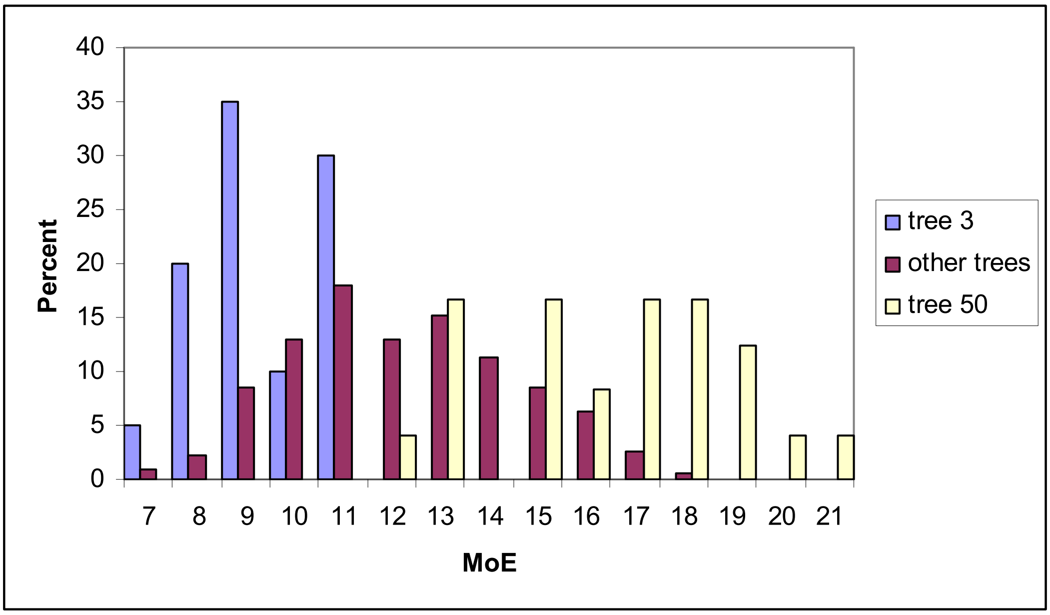


**Fig. 8: MoE distributions for timber from the best and worst trees in the study (trees 50 and 3), and the remaining 16 trees.**

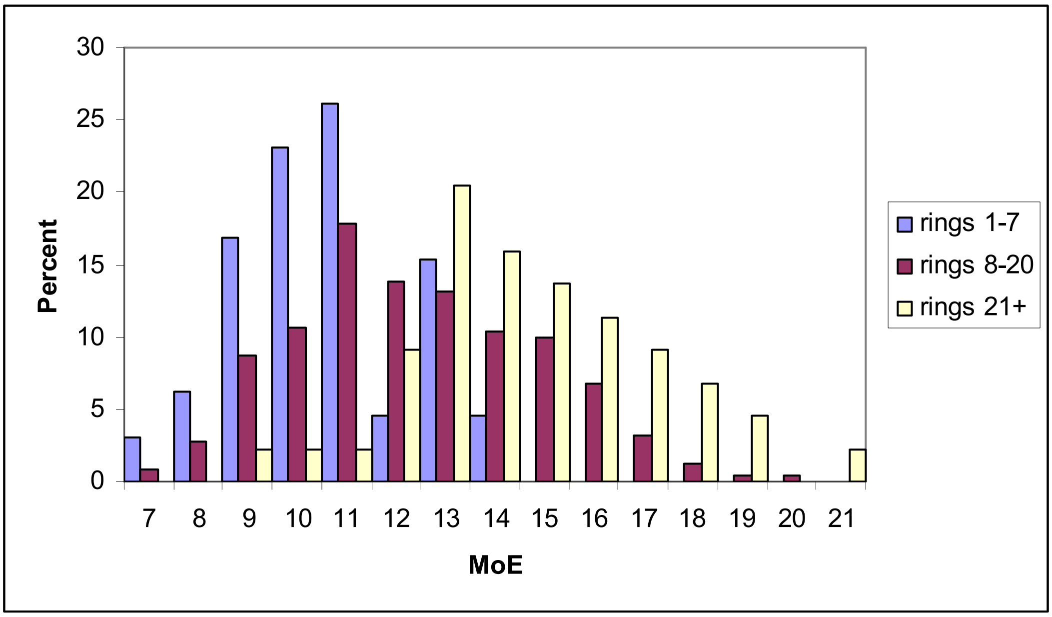


**Fig. 9: MoE distributions for timber from the inner 7 rings, rings 8-20, and rings 21+.**

Tree means of important variables are shown in Appendix 1 and correlations among these are shown in Appendix 2. A number of general observations can be made from these correlations:

- There were high correlations among all three sampling methods for MoE.
- There were also high correlations among all sampling methods for Density.
- MoE was highly positively correlated with density and weakly negatively correlated with MFA.
- Timber MoE was weakly negatively correlated with branch index.
- MoE was strongly correlated with small clears MoR and but less strongly with timber MoR.
- The correlation between MoE and the sound velocity stiffness index was weaker than MoE/density correlation. On the basis of this study, sound velocity does not provide a better prediction of stiffness than density.
- There was a weak negative correlation between Density and MFA in this study, meaning that trees selected for higher density would tend also to have lower MFA.

Regressions between timber and clear wood MoE and other variables were derived. These were also based on the tree mean values of each variable.

Small clears stiffness was strongly related to small clears density ($R^2 = 0.84$), and only weakly related to MFA ($R^2 = 0.32$). A multiple regression including both small clears density ($t_{15} = 8.86$; $p < 0.0001$) and MFA ($t_{15} = -2.50$; $p = 0.024$) had an $R^2$ of 0.89:

$$\text{Small\_clears\_MoE} = 1.87 + 0.0293\ \text{Small\_clears\_Density} - 0.317\ \text{MFA}$$

Because of the small variation between trees in MFA and the relatively large variation in density in this study (Table 1), the high correlations between tree mean MoE and density, and relatively low correlations with MFA are not surprising. It is not clear whether the low between-tree variance in MFA found in this study is typical. However, the correlations between density and MoE are unusually high compared with previous studies. This suggests that a greater between-tree variance in MFA may be more typical. Also, the fact that trees in this study were deliberately chosen to cover a range of densities would tend to exaggerate the density effect.

Timber stiffness was strongly related to density ($R^2 = 0.73$), but slightly more strongly related to small clears stiffness ($R^2 = 0.75$) and only weakly related to branch index ($R^2 = 0.24$). A multiple regression including both small clears MoE ($t_{15} = 7.53$; $p < 0.0001$) and branch index ($t_{15} = -2.97$; $p = 0.0095$) had an $R^2$ of 0.84:

$$\text{Timber\_MoE} = 5.39 + 1.19\ \text{Small\_clears\_MoE} - 1.04\ \text{BIX}$$

This regression clearly demonstrate that clear wood stiffness is the most important component controlling timber stiffness in these trees, but that there is a secondary branch diameter effect. The variance explained by this equation is much better than in most previous attempts to model timber stiffness.

Combining the above two equations gives the following equation which best reflects the relative contributions of density, branch diameter (Branch Index, or BIX), and MFA on tree mean timber MoE:

$$\text{Timber\_MoE} = 7.62 + 0.0349\ \text{Density} - 0.377\ \text{MFA} - 1.04\ \text{BIX}$$

This equation implies that an increase in the mean MoE of 1 Gpa can be achieved by increasing mean tree wood density by 30 $kg/m^3$, reducing mean MFA by 2.6°, or reducing BIX by 1 cm.

When selecting trees for breeding purposes, it is likely that only breast height samples of density, some sound velocity-based measure of stiffness, and possibly a breast height estimate of MFA, along with BIX will be available to the researcher. In this study, timber MoE was quite highly correlated with breast height outerwood density (BHO_Density), and weakly correlated with BIX (Appendix 2). The following equation had an $R^2$ of 0.64:

$$\text{Timber\_MoE} = 5.66 + 0.030\ \text{BHO\_Density} - 1.0\ \text{BIX}$$

However, the IML stiffness index performed much more poorly than density ($R^2 = 0.34$), and breast height MFA was not significantly correlated with MoE at all. Thus, at this stage, it must be concluded that these new tools for testing wood stiffness have yet to prove themselves to be superior to traditional measurements in the selection of superior Douglas-fir trees.

## Conclusions

Using the above analyses, it is possible to estimate the contribution to the variance in stiffness between pieces of Douglas-fir timber of the most important components.

- About 35% of the variance in timber stiffness can be attributed to a tree effect. It is this tree component which is most amenable to improvement by tree breeding. Based on this sample of trees, at least 75% of this effect can be related directly to clearwood stiffness, and an additional 10% to branch diameter. The remaining 15% may be largely experimental noise. The majority of the variation in stiffness of small clears in this study could in turn be related to density, with only a small percentage, perhaps 5% to 10% related to MFA.

- About 27% of the variance in timber stiffness can be attributed to a general pattern based on position within the tree. About 90% of this variance is associated with ring age, and the rest with height. This variation in stiffness is probably primarily related to MFA and to a lesser extent, density. This can be inferred from the relatively small within-tree variation in density compared with MFA. Theoretically, there is some possibility of reducing this variance through tree breeding by producing trees with less pith-to-bark variation in density, and especially in MFA.

- About 10% of the variance in stiffness is associated with interactions between the tree and the within-tree components. This is caused by differences between individual trees in the relationships between MoE and ring number or height.

- The remaining variance (about 28%) is presumably associated with random piece-to-piece variation in clear wood stiffness and knot distribution over and above the tree mean and position effects.

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## Appendix 1: Tree Mean Parameters

Predicted tree mean MoE Density and MoR were calculated from the nonlinear models. For convenience, these were standardised these to predict the mean for each tree for ring 20 at breast height (1.4 m). Also included are outerwood breast height disc density, IML sound velocity, and Silviscan MFA of the outer rings at breast height.

| Tree | Small clears | | | Timber | | Silviscan | | | | Sound velocity | BHO Density | DBH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MoE | MoR | Density | MoE | MoR | MoE | MFA | BHO MFA | Density | | | |
| 3 | 8.92 | 74.7 | 397 | 12.37 | 25.5 | 10.89 | 12.97 | 15.61 | 438 | 3110 | 344 | 42.0 |
| 9 | 10.81 | 88.4 | 441 | 15.86 | 33.2 | 15.24 | 11.57 | 11.46 | 515 | 3406 | 445 | 43.2 |
| 15 | 10.85 | 89.0 | 458 | 14.67 | 37.3 | 13.77 | 11.77 | 11.00 | 509 | 3556 | 427 | 40.1 |
| 16 | 12.48 | 97.6 | 470 | 16.93 | 41.6 | 18.02 | 10.57 | 10.49 | 557 | 3506 | 435 | 45.0 |
| 19 | 13.17 | 101.8 | 502 | 17.31 | 36.5 | 17.85 | 11.30 | 13.14 | 588 | 3250 | 480 | 49.0 |
| 22 | 11.41 | 87.7 | 454 | 14.89 | 39.6 | 14.73 | 13.13 | 10.01 | 492 | 3558 | 403 | 37.6 |
| 23 | 12.10 | 102.1 | 503 | 16.81 | 42.3 | 15.56 | 13.09 | 11.49 | 577 | 3422 | 472 | 38.8 |
| 27 | 12.02 | 94.2 | 461 | 16.61 | 33.8 | 17.45 | 10.40 | 9.57 | 547 | 3358 | 482 | 44.0 |
| 28 | 11.31 | 83.9 | 428 | 14.40 | 42.4 | 13.89 | 11.93 | 10.46 | 503 | 3461 | 450 | 51.2 |
| 31 | 11.37 | 91.3 | 458 | 15.41 | 44.2 | 16.01 | 11.86 | 10.63 | 549 | 3139 | 466 | 49.6 |
| 34 | 9.94 | 76.6 | 415 | 14.17 | 36.0 | 14.40 | 11.56 | 11.14 | 483 | 3187 | 416 | 51.2 |
| 38 | 11.38 | 89.9 | 463 | 13.49 | 35.6 | 14.81 | 12.08 | 10.69 | 532 | 3493 | 451 | 46.2 |
| 39 | 11.39 | 87.0 | 453 | 13.56 | 30.3 | 15.05 | 12.80 | 12.18 | 521 | 3067 | 420 | 50.5 |
| 40 | 9.77 | 76.9 | 398 | 13.18 | 26.0 | 12.94 | 13.59 | 11.88 | 470 | 3007 | 379 | 45.3 |
| 42 | 11.78 | 94.3 | 476 | 15.32 | 31.5 | 15.44 | 11.72 | 11.51 | 542 | 3611 | 488 | 46.7 |
| 43 | 13.85 | 106.6 | 502 | 17.80 | 47.6 | 18.32 | 10.80 | 10.31 | 583 | 3783 | 499 | 38.3 |
| 48 | 12.10 | 93.5 | 468 | 16.64 | 38.6 | 16.58 | 11.12 | 11.00 | 550 | 3563 | 435 | 39.4 |
| 50 | 13.19 | 108.2 | 521 | 19.58 | 60.8 | 17.13 | 11.84 | 13.84 | 604 | 3219 | 482 | 47.5 |
| Mean | 11.55 | 91.3 | 459 | 15.50 | 37.9 | 15.45 | 11.89 | 11.47 | 531 | 3372 | 443 | 44.8 |
| CV | 10.8 | 10.6 | 7.6 | 12.0 | 21.8 | 12.5 | 7.7 | 12.9 | 8.3 | 6.4 | 9.2 | 10.3 |

CV – coefficeint of variation = sd /mean x 100.

## Appendix 2: Pearson Correlations Among Tree Means

| | MoE | | | V | IML | MoR | | Density | | | MFA | | BIX |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | T | SC | S | | | T | SC | SC | S | BHO | S | BHO | |
| MoE SC | 0.86** | | | | | | | | | | | | |
| MoE S | 0.85** | 0.91** | | | | | | | | | | | |
| V | 0.60** | 0.74** | 0.61** | | | | | | | | | | |
| IML | 0.36 | 0.50* | 0.39 | 0.92** | | | | | | | | | |
| MoR T | 0.78** | 0.69** | 0.57* | 0.48* | 0.30 | | | | | | | | |
| MoR SC | 0.91** | 0.95** | 0.85** | 0.72** | 0.46 | 0.72** | | | | | | | |
| Dens SC | 0.85** | 0.92** | 0.80** | 0.70** | 0.44 | 0.70** | 0.98** | | | | | | |
| Dens S | 0.89** | 0.94** | 0.89** | 0.64** | 0.34 | 0.70** | 0.97** | 0.95** | | | | | |
| Dens BHO | 0.75** | 0.83** | 0.80** | 0.78** | 0.46 | 0.58* | 0.83** | 0.81** | 0.88** | | | | |
| MFA S | -0.58* | -0.56* | -0.73** | -0.57* | -0.47 | -0.33 | -0.48* | -0.40 | -0.53* | -0.59** | | | |
| MFA BHO | -0.10 | -0.26 | -0.38 | -0.48* | -0.54* | -0.13 | -0.12 | -0.09 | -0.16 | -0.37 | 0.38 | | |
| BIX | -0.49* | -0.23 | -0.23 | -0.53* | -0.52* | -0.35 | -0.36 | -0.30 | -0.24 | -0.30 | 0.24 | 0.26 | |
| DBH | -0.18 | -0.12 | -0.03 | -0.35 | -0.58* | -0.03 | -0.22 | -0.19 | -0.02 | 0.09 | -0.06 | 0.14 | 0.63** |

***The following codes are used:***
MoE = Modulus of elasticity (stiffness)
MoR = Modulus of rupture (strength)
MFA = Microfibral angle
IML = IML sound velocity
V = Stiffness index derived from sound velocity = $IML^2$ x BH_Density
BIX = Branch index (mean diameter of largest branch per quartile of each log)
T = Whole tree estimates standardised to breast height, ring 20, based on timber pieces cut from 4.8 m logs
SC = Whole tree estimates standardised to breast height, ring 20, based on small clears cut from billets
S = Whole tree estimates standardised to breast height, ring 20, based on Silviscan cores
BH = Breast height disc sample
BHO = Sample taken from outer rings of breast height core
* significant at p = 0.05
** significant at p = 0.01