IAWA Journal, Vol. 23 (3), 2002: 253–265

# RELATIONSHIP BETWEEN WOOD DENSITY, MICROFIBRIL ANGLE AND STIFFNESS IN THINNED AND FERTILIZED PINUS RADIATA

by

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## SUMMARY

The relationships between wood anatomy in standing trees and the strength of boards were examined in *Pinus radiata* D. Don (thinned vs thinned and fertilized) at 2 contrasting sites. Fertilizer treatments were applied after mid-rotation thinning. Logs were taper sawn and boards, near the pre-treatment/post-treatment boundary, subjected to acoustic and strength assessment. Average wood property data from a 12-mm increment core obtained prior to harvest, was extracted from the relevant portion of the radius.
In general, fertilizer resulted in lower density, higher microfibril angle (MFA) and slightly lower stiffness. However, stiffness was still relatively high as the affected wood was from the more mature portion of the radius. SilviScan density and MFA data were good predictors of stiffness. Acoustic measurements on boards were strongly correlated with board stiffness. Path analyses explained up to 45% of the variance in stiffness, as a function of estimated MOE and log sweep.

***Key words:*** Density, microfibril angle, stiffness, fertilizer, SilviScan, *Pinus radiata.*

## INTRODUCTION

Stiffness is a major quality determinant of structural grade timber that defines the dollar value of the output for the saw-miller. In general terms, the saw mill purchases logs at a set rate, based largely on volume, and derives its economic return from the volume and strength of timber produced. Thus, for the raw material input to the mill, wood cost is defined by log volume. However, the output value is determined by both the volume of boards and their quality, in this case strength or stiffness.

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As growers increase the growth rate of plantation *Pinus radiata* D. Don, rotation lengths shorten and the proportion of lower strength juvenile wood increases. Consequently, the output volume of the higher strength grades decrease. This is perceived by the sawmill as a decrease in density mediated by fast growth. Thus, fast growth becomes synonymous with lower density, lower stiffness and higher juvenile wood proportion. However, the evidence indicates that shorter rotation lengths are the cause of the density decrease, not growth rate. Previous studies have indicated very little direct relationship between increasing growth rate and decreasing density (Larson 1969; Zobel & Van Buijtenen 1987; Nyakuengama et al. in prep.). In general, increases in growth rate have been mediated through tree breeding and improved silviculture, particularly silviculture during establishment and leading up to canopy closure. Growth increases have often had their dominant effect in maximising the volume of the juvenile core.

Recently there has been a growing focus on improving growth during mid-rotation, where volume gains maximise the production of higher quality outer wood (Nyakuengama et al. in prep.). The question arises with this strategy as to whether the growth gains actually do adversely affect timber strength. Recent work has shown that density can locally decrease in response to these treatments, but that at the level of the whole log, the reductions were not statistically significant (Nyakuengama et al. 2002). Whether these reductions, in the order of 30 kg/m$^{-3}$, are commercially significant requires further study.

In this study, the strength of boards from nitrogen and phosphate fertilizer treatments, applied in mid-rotation at two sites, were investigated. Boards obtained from the affected portion of the radius were strength tested. The relationship between stiffness and wood properties, measured in increment core samples taken prior to harvest, was then determined.

## EXPERIMENTAL DESIGN

### *Site description*

The investigation used two *Pinus radiata* plantations located at Longford (VRK142) and Carabost (N10141). The Longford site (Australian Paper Plantations) is located in south-east Gippsland, Victoria (38° 16' S, 146° 40' E). The Carabost site (New South Wales State Forests) is located 23 km north-west of Tumbarumba, New South Wales (147° 48' E, 35° 39' S). Nitrogen (N) and phosphorus (P) were the main fertilizer treatments. Both sites had a measurable growth response to fertilizer (minimum of 6 m$^3$ ha$^{-1}$ in 7 years) and at least 5 years of post-treatment growth.

Four contrasting fertilizer treatments were applied following thinning at each site (control, N, P and NP). The Longford plantation was established in 1972, non-commercially thinned in 1978 (age 6) and thinned prior to fertilizer application in 1986 (age 14). Fertilizer application rates were nil and 100 kg ha$^{-1}$ P and 200 kg ha$^{-1}$ N (Pongracic et al. 1995). In addition, all treatments received 100 kg ha$^{-1}$ K and the P treatment received 100 kg ha$^{-1}$ Ca. The Carabost plantation was established in 1965 and thinned immediately prior to fertilizer application in 1982 (age 17). Fertilizer application rates were nil and 225 kg ha$^{-1}$ for both N and P (Carter 1985). The treatments were assessed for wood property responses to treatments utilising 12 mm increment cores as described in Nyakuengama et al. (2002) and Nyakuengama et al. (submitted), along with more detailed site and silvicultural information.

### *Harvest and log preparation*

Sixty-four trees from each site were felled and a 5-m long butt log prepared for sawing. Of these, 48 had 12 mm increment cores extracted previously at breast height, 18 and 6 months prior to harvest at Longford and Carabost respectively. Logs from only 2 of the 4 treatments (32 thinned control vs 32 thinned, NP fertilized) at each of 2 sites were harvested and the amount of sweep recorded in each log. The 128 logs were transported to the Timber Industry Training Mill at Creswick, Victoria and prepared for sawing.

In each log the pre-/post-treatment boundary was identified, as was the orientation from which the increment core was taken. The face of one end of the log, closest to the increment core hole, was painted as shown in Figure 1a. Each log was taper sawn individually through the mill. Boards of 102 × 40 mm nominal dimensions were sawn and every board marked with respect to its original position in the log. For the purposes of the study described here, only boards from the increment core axis were examined further (Fig. 1b).

### *Assessment of board and wood property measurement*

The acoustic properties of timber are increasingly being used to provide rapid predictions of log and timber stiffness. The velocity of sound in wood has been shown to correlate well with stiffness (Tsehaye et al. 2000). Acoustic properties of the green boards were determined using a Fakopp testing system (Dickson et al. 2000). Sawn boards were then transported to the mill at Brown and Dureau, Morwell, Victoria and dried to 10–12% moisture content. Each board was then stress graded and boards selected from the post-treatment portion of the radius (Fig. 1b). These boards were subjected to a 4-point static bending test performed to obtain MOE immediately (300 mm) above the increment core hole, MOE at a random position along the board, and MOR at that randomly selected point. Visual defects such as knots and wane were recorded for each board where they corresponded to the grade limiting section (i.e. weakest point) of the board. Of the 128 logs harvested, 96 had wood property data available from previous SilviScan analyses (Nyakuengama et al. 2002) of increment cores (48 per site; 24 per treatment). From each log, one board was extracted, from the portion of the radius that corresponded as closely as possible to the time immediately following thinning and fertilisation (Fig. 1b). Some boards included a portion of pre-treatment wood and this amount was recorded in every board at both ends.

Previous studies had examined the wood properties of these trees (Nyakuengama et al. 2002; Nyakuengama et al. submitted), and pith to bark profiles of density, fibre size, wall thickness and coarseness were available. In addition microfibril angle (MFA)

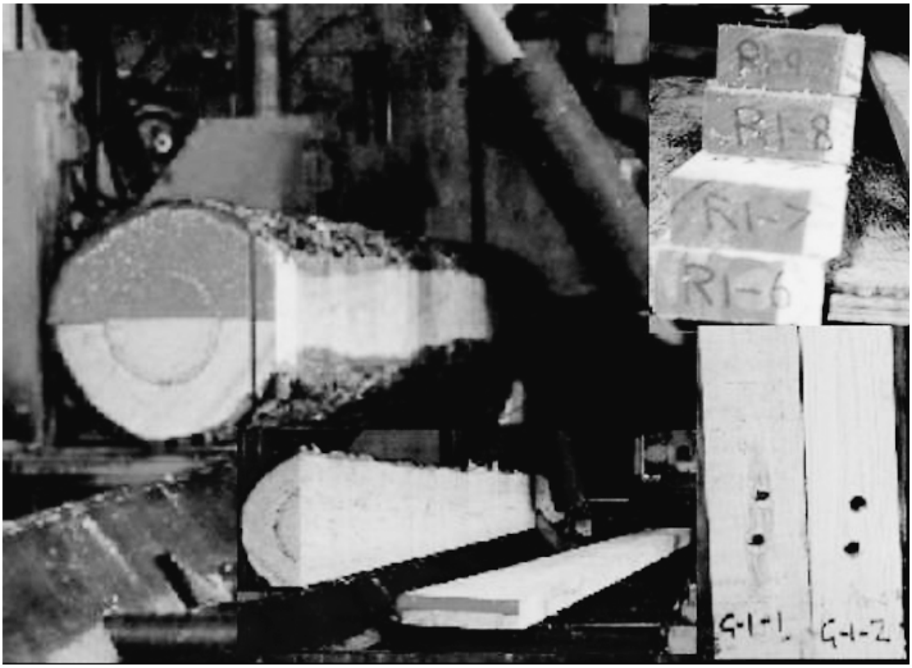

Fig. 1a. The northern half of each log face was painted, with the boundary indicating the orientation from which the increment core was taken. Boards from this axis were characterised by the holes left from the coring process.

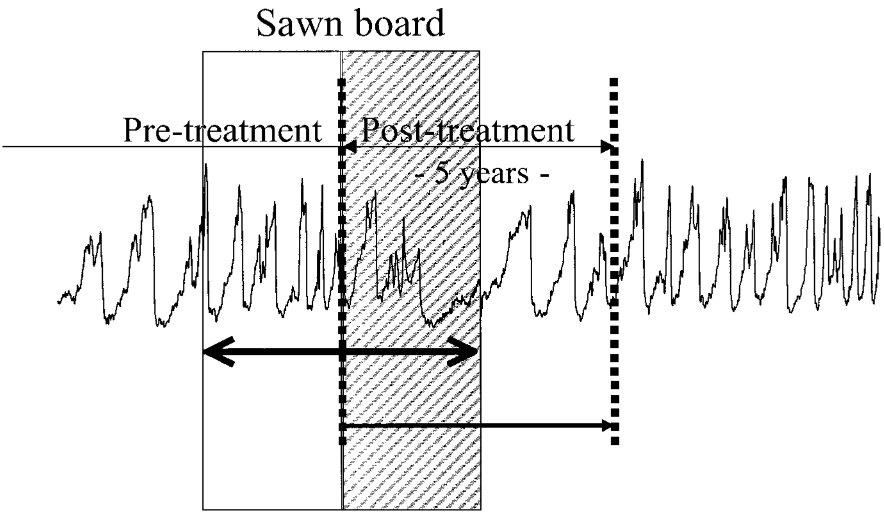

Fig. 1b. The position of the data extracted from the radial profiles was adjusted for the amount of pre-treatment wood in the board, recorded during the sawing study.

and estimated stiffness (est.-MOE) were assessed in the stored samples relating to the logs examined in this study using SilviScan (Evans 2000). Estimated stiffness was determined from a combination of the density data and the X-ray diffraction pattern obtained during the MFA analysis. The radial profiles of MFA and est.-MOE were obtained at 1 mm radial increments.

Using the sawn board dimensions and the proportion of the board width containing pre-treatment timber, the MFA, density and stiffness data was extracted from the radius that most closely matched the sawn board (Fig. 1b). Software written in IDL (Interactive Data Language, Research Systems Inc.) was used for this process.

### *Data analysis*

Treatment effects on measured board properties were compared using analysis of variance procedures. The measured stress grade, MOE and MOR of each board was related to the wood properties (density, MFA and est.-MOE) using correlation analyses (Statistica 1999). Correlation analyses do not separate direct from indirect relationships. For example the ring width to ring density relationship from pith-to-bark in a single radius is largely indirect. To control for effects of common variance, path analysis was used as an extension of multiple regression.

Path analysis is an analytical method that allows covariance between independent variables to be taken into account when defining causal relationships. It involves the definition of a preconceived causal model (see Fig. 3a) in which independent variables (LHS) drive variation in dependent variables (RHS). Board stiffness was a dependent variable and regressed on the independent wood variables (MFA, density) that were assumed to affect it. The resulting standardised regression weights indicate the strength and direction of the relationships among the hypothesised variables (Leong & Austin 1996). The model was examined to see how well it fitted the data using the chi-square test to test goodness-of-fit. Through path analysis the magnitudes of the linkages between variables were estimated (Miller & Jastrow 1990). EQS for Windows, Ver. 5.7 was used for correlation and path analysis (Bentler & Wu 1995; Bentler 1998).

## RESULTS

Given the difference in tree age and the ages at which treatments were applied, each site was examined independently. Treatment means for each site are shown in Tables 1a & b, significant treatment effects were evident for different wood and board properties. At both sites, the fertilized treatment had lower density and estimated MOE and increased MFA (at Longford $p = 0.08$ for MFA).

At Longford no significant differences in actual board MOE or MOR were observed. In contrast, the fertilized treatment at Carabost was significantly weaker. Log sweep was included in the tables, given the potential effect it could have on grain and microfibril angle (Fig. 2). Within the Carabost data log sweep was predominantly zero. In contrast, the Longford data exhibited a normal distribution, but no significant effect of treatment was apparent.

Table 1. Treatment means and effects on wood and board properties for (a) the Longford site and (b) the Carabost site. The first 3 rows describe data extracted from the radial profile at the position from which boards were obtained. The last 5 rows describe actual board properties.

**a)**

| Property | Longford | | Treatment effect |
|---|---|---|---|
| | Control | Fertilised | p |
| Average Density (kg/m$^3$) | 596 | 566 | 0.027 |
| Average MFA (degrees) | 19.8 | 22.0 | 0.080 |
| Average Est. stiffness (GPa) | 14.0 | 12.2 | 0.030 |
| Acoustic test (green) | 3523 | 3488 | ns |
| Actual MOE (GPa) | 11.73 | 11.36 | ns |
| Actual MOE random (GPa) | 12.08 | 11.49 | ns |
| Actual MOR random (GPa) | 54.56 | 54.57 | ns |
| Log sweep (degrees) | 5.33 | 4.52 | ns |

**b)**

| Property | Carabost | | Treatment effect |
|---|---|---|---|
| | Control | Fertilised | p |
| Average Density (kg/m$^3$) | 548 | 507 | < 0.001 |
| Average MFA (degrees) | 18.0 | 20.3 | 0.029 |
| Average Est. stiffness (GPa) | 13.6 | 11.8 | 0.002 |
| Acoustic test (green) | 3712 | 3607 | 0.064 |
| Actual MOE (GPa) | 13.47 | 11.87 | 0.001 |
| Actual MOE random (GPa) | 13.20 | 11.44 | 0.004 |
| Actual MOR random (GPa) | 69.47 | 57.02 | 0.058 |
| Log sweep (degrees) | 1.0 | 1.0 | ns |

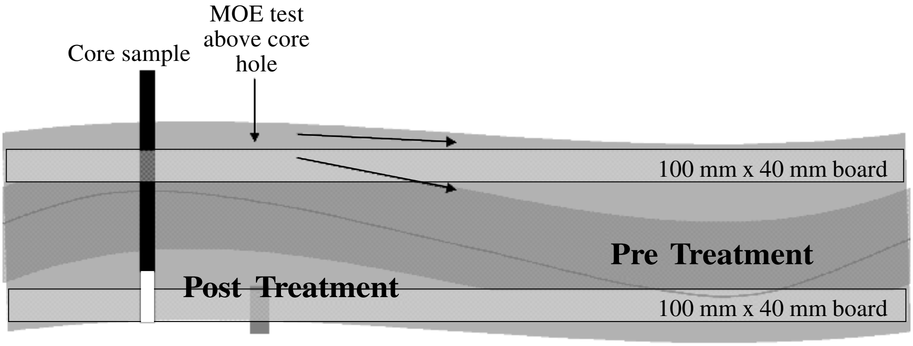

Fig. 2. The potential effect of log sweep on grain angle (arrows) in the board is illustrated, which may add variance to the relationship between board strength and wood properties in increment cores.

### *Path analysis*

In this analysis the data from all boards were combined independent of site and treatment on the basis that these factors contributed to the variance in the data but were otherwise irrelevant in terms of the proposed model. The objective here was to explain board strength in terms of wood properties independent of site and treatment.

The wood properties measured by SilviScan were used as independent variables to predict board strength. Log sweep was included to provide some measure of the effect of changing grain angle on stiffness independent of its effects on density and MFA. The co-variance (curved arrows) between density, MFA and log sweep indicated small correlations between them (Fig. 3a). The figures associated with the curved arrows are simple correlation coefficients. The straight arrows imply a direct effect with changes in variables on the left directly causing changes in variables on the right. The numbers (path coefficients) associated with these arrows are standardized partial regression coefficients, and indicate the amount of change expected by changes in the wood properties, in terms of standard deviations. For example an increase in density of 1 standard deviation would cause an increase of 0.42 standard deviations in the actual board MOE above the core hole (Fig. 3a), other factors remaining constant.

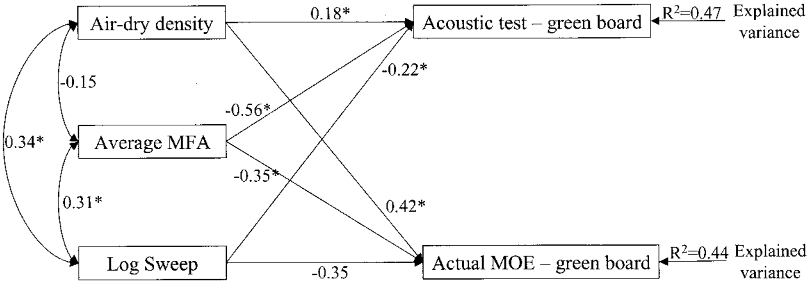

Fig. 3a. The relationships between two independent (LHS) and dependent (RHS) variables using path analysis. The model was significant at P < 0.001 with a Chi Square goodness of fit of 49.4. Asterisks denote relationships that are statistically significant at the 95% level.

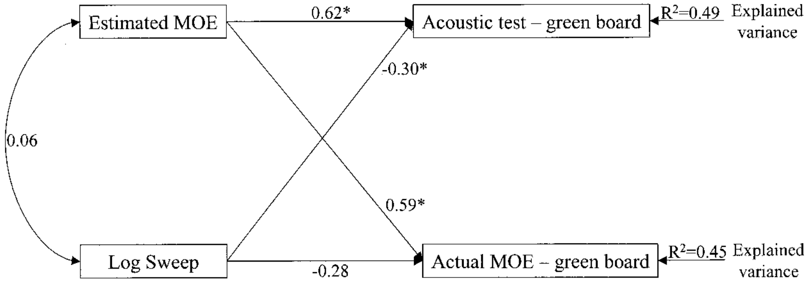

Fig. 3b. The relationships between the independent (LHS) and dependent (RHS) variables using path analysis, mediated by estimated MOE. The model was significant at P < 0.00 with a Chi Square goodness of fit of 37.0. Asterisks denote relationships that are statistically significant at the 95% level.

In generating the path coefficients, the variance explained by the partial correlations between the independent variables is controlled. Density, MFA and log sweep together explained 44% of the variance in actual board MOE. MFA contributed most towards this explained variance as indicated by the product of the path coefficient (0.35) and the correlation coefficient between MFA and actual MOE (-0.52, Table 2).

Table 2. Correlations (r) between board and SilviScan data, combining sites and treatments.

| | Air dry density | MFA | Estimated MOE | Acoustic test (green) | Log sweep |
|---|---|---|---|---|---|
| MOE above core hole | 0.36 | -0.52 | 0.61 | 0.79 | -0.31 |
| MOE random | 0.41 | -0.45 | 0.58 | 0.69 | -0.25 |
| MOR random | ns | ns | ns | 0.38 | -0.21 |
| Acoustic test (green) | ns | -0.65 | 0.63 | | -0.33 |
| Log sweep | 0.34 | 0.31 | ns | -0.35 | |

All correlations shown are significant at the p = 0.05 level. Correlations greater than 0.35 are significant at $p < 0.001$; N = 91.

The estimated MOE values by SilviScan were calculated independently of density and MFA but are highly correlated with them (Table 2). Regression analyses (not shown) indicated density and MFA explained 96% of the variance in estimated MOE. In essence this variable is a mass weighted MFA providing information not only about the MFA but also the proportion of the cell wall mass represented by orientated material (Evans & Ilic 2001). In Figure 3b the effect of using estimated MOE is shown in place of density and MFA. The variance explained by both density and MFA is effectively combined into a single variable which was as effective in explaining actual MOE. The inclusion of estimated MOE did not markedly reduce the direct effect of log sweep on actual board MOE. This model explained approximately 50% of the variance in the acoustic data (Fig. 4a, b) of which 39% could be attributed to estimated MOE.

### ***Relationships within sub-populations***

Correlations between variables were examined as a whole (Table 2) and then partitioned into site × treatment populations (Table 3). The relationship between density was significant and of similar magnitude at both sites. The est.-MOE was more highly correlated with actual MOE than was MFA for both sites, particularly in the control treatments. MFA was significantly correlated with board strength in the Longford data but not in the Carabost data. Within the Longford data both MFA and est.-MOE exhibited strong correlations within both treatments; the relationships being strongest in the control treatment. However, these relationships were weaker in the Carabost data. In these variables the range and variances were slightly greater at Longford than at Carabost (Fig. 4). In general Carabost boards had a slightly lower density and the strength range did not extend as high as those seen in the Longford boards. Variance in estimated MOE explained more variance of actual MOE at Longford (53%) than

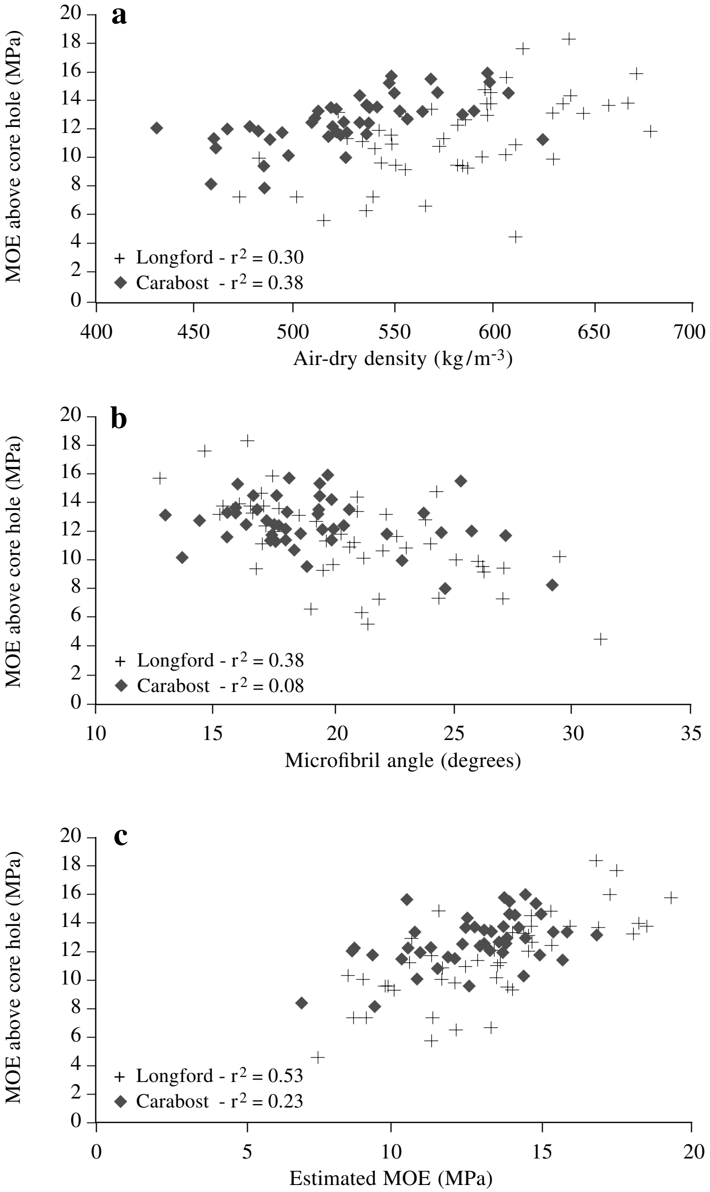

Fig. 4. Relationships between Actual board MOE and a) density, b) MFA, and c) estimated MOE for each site.

density (30%) or MFA (38%). In contrast, at Carabost density variation explained more variance (38%) than MFA (8%) or estimated MOE (23%). Log sweep was not significantly correlated with any of the wood and strength variables within the Longford data, but was positively correlated with MFA at Carabost.

Acoustic measurements on the green boards also correlated with board MOE (Table 2). From the SilviScan data it can be seen that the acoustic test itself was correlated most strongly with MFA. Acoustic tests were no more effective in predicting strength in the Carabost board than SilviScan variables. As the acoustic measurements were made directly on the green boards, this suggests that the poor explanatory power of the SilviScan data was not a consequence of a poor matching of wood properties, extracted from the increment core radius, with the actual board position. The correlations at both sites were most significant in the control treatments (Table 3).

Table 3. Correlations (r) between board and SilviScan data from the (a) Longford control, (b) Longford fertilizer, (c) Carabost control and (d) Carabost fertilizer treatments.

| | Air dry density | MFA | Estimated MOE | Acoustic test (green) | Log sweep |
|---|---|---|---|---|---|
| **a)** Longford control (n = 24) | | | | | |
| MOE above core hole | 0.55 | -0.77 | 0.84 | 0.91 | ns |
| MOE random | 0.60 | -0.72 | 0.86 | 0.86 | ns |
| MOR random | ns | -0.59 | 0.54 | 0.65 | ns |
| Acoustic test (green) | 0.44 | -0.91 | 0.90 | 1 | ns |
| Log Sweep | ns | ns | ns | ns | 1 |
| **b)** Longford fertilized (n = 23) | | | | | |
| MOE above core hole | 0.57 | -0.43 | 0.61 | 0.86 | ns |
| MOE random | 0.47 | ns | 0.45 | 0.65 | ns |
| MOR random | ns | ns | ns | ns | ns |
| Acoustic test (green) | 0.51 | -0.55 | 0.64 | 1 | ns |
| Log Sweep | ns | ns | ns | ns | 1 |
| **c)** Carabost control (n = 22) | | | | | |
| MOE above core hole | 0.66 | ns | ns | ns | ns |
| MOE random | ns | ns | ns | ns | ns |
| MOR random | ns | ns | ns | ns | ns |
| Acoustic test (green) | ns | -0.54 | 0.62 | 1 | ns |
| Log Sweep | ns | ns | ns | ns | 1 |
| **d)** Carabost fertilized (n = 22) | | | | | |
| MOE above core hole | 0.44 | ns | 0.48 | 0.48 | ns |
| MOE random | 0.46 | ns | 0.47 | 0.52 | ns |
| MOR random | ns | ns | ns | ns | ns |
| Acoustic test (green) | ns | ns | 0.49 | 1 | ns |
| Log Sweep | ns | ns | ns | ns | 1 |

All correlations shown are significant at the $p = 0.05$ level. Correlations greater than 0.7 are significant at $p < 0.001$.

## DISCUSSION

Significant relationships between wood properties, determined in increment cores from trees prior to harvest, and board strength were found. Fertilizer treatments at the two sites resulted in changes in board strength but these changes were relatively small in magnitude. Boards from the portion of the log affected by the fertilizer/thinning treatment were 12% less stiff in the fertilized trees from Carabost, but actual board stiffness was unaffected at Longford. Correlations between wood and board properties differed in strength between sites and between fertilizer treatments within sites. At Carabost, density variation was most highly correlated with actual board MOE, while at Longford estimated MOE had the higher correlation with actual board MOE. Combining independent variables to predict board strength using path analysis did not markedly improve the explanation of variance compared to the use of single predictive variables. The lack of covariance between density and MFA indicate the independent contributions each of these properties made to board strength. Acoustic measurements made directly on the green boards were found to be good predictors of board stiffness. The wood properties in turn were also good predictors of acoustic properties, providing some explanation of the latter's effectiveness.

Over recent years there has been an increasing focus on wood microfibril angle and stiffness as a selection indicator of wood quality that is as important, if not more important than density (Tseyahe et al. 1987; Dickson & Walker 1997). Megraw et al. (1999) found in loblolly pine that stiffness variation was best explained by a combination of basic density and microfibril angle. The role of microfibril angle was recently reviewed by Cave and Walker (1994) who observed 5 to 6 fold increases in stiffness arising from changes in MFA from 10 to 40 degrees. Similarly a review by Walker and Butterfield (1996) concluded that in radiata pine the "intrinsic characteristic that is likely to yield the greatest economic benefits is the microfibril angle." The reason for the lack of correlation between MFA and actual board stiffness in the Carabost data is unknown. The small but significant influence of log sweep on board stiffness was evident in the path analysis results. This probably reflects changes in grain angle and fibre orientation.

There is increasing interest in the application of acoustic analysis as a means of predicting log and board strength (Schad et al. 1995; Rajesjwar et al. 1997; Marchal & Jacques 1999). Karsulovic et al. (1987) showed that the speed of propagation of stress waves were an excellent predictor of MOE in radiata pine timber. These velocities are affected by grain angle (Wang 1984; Suzuki & Sasaki 1990; Holz & Kluck 1997) and moisture content (Sasaki et al. 1988; Nakamura & Nanami 1993). The relationship with density is less clear. Wang (1984) found no relationship between sound velocity and density in 16 species, in contrast to Schad et al. (1995) who reported a useful correlation. In this study, the Fakopp measurement of stress wave velocity was significantly correlated with actual board stiffness. Half the variance in these acoustic measurements were, in turn, explained by density, MFA and MOE estimated by SilviScan. In general the relationship was weaker in boards from the fertilized trees.

In conclusion, the density, MFA and MOE determined by SilviScan in increment cores was found to correlate with the stiffness of boards taken from the portion of the stem radius affected by mid-rotation fertilisation and thinning. At one site (Longford) density, MFA and stiffness were all correlated to actual board MOE, while at the other site (Carabost) density was the dominant correlate. Acoustic tests made on the actual boards were also useful predictors of board stiffness, and the SilviScan data indicated that these tests were, in turn, best related to MFA variation. Fertilizer application caused slight reductions in strength, although strengths were still relatively high. This is because the wood production affected by the treatment is in the mature wood zone where density is higher and MFA lower than in the juvenile zone. The economic significance of this at a commercial scale requires further analysis.

## ACKNOWLEDGEMENTS

This study was developed from a joint research project between the FWPRDC, CSIRO Forestry and Forest Products and industry partners; Australian Paper Plantations, Fletcher Challenge Paper, Hancock's Victoria Plantations, NSW State Forests and Carter Holt Harvey. Thanks to Drs Laurie Schimleck, Carolyn Raymond and Les Groom for valuable comments on the manuscript.

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