MODELLING *PINUS RADIATA* LUMBER CHARACTERISTICS. PART 1: MECHANICAL PROPERTIES OF SMALL CLEARS

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ABSTRACT

Fast-grown plantation wood (particularly the juvenile zone) can have some limiting performance characteristics (stiffness, strength, stability). Improvements in the overall performance of the lumber products will depend on a knowledge of the most important factors which can be influenced by either silviculture or tree breeding. Some wood technologists believe that the traditional view of wood density as the single most-important factor may be flawed, and that other parameters (e.g., microfibril angle, spiral grain, and compression wood) may have an equal or greater effect.

During 1996–98, intensive utilisation studies were carried out on *Pinus radiata* D.Don material from two sites in the central North Island of New Zealand. Sample trees were selected from managed crops (23 and 28 years old respectively) to cover a range of wood properties. They were chosen on the basis that they represented a wide range of tree characteristics (diameter, branch habit), and subsequently the full range of log and stem properties was measured from wood disc samples and sawn lumber. One of the objectives of the research was to document the relative importance of a number of properties known to influence both mechanical properties and product performance.

Some of the studies comprised a series of standard "small clears" tests, designed to untangle the impacts of wood density, ring width, spiral grain, compression wood, and microfibril angle on bending strength (MoR) and stiffness (MoE). Altogether 450 "small clears" samples were selected, covering the range of log and lumber properties existing in 51 stems from 15 clones across the two trials. Each wood sample was designated "juvenile" (within 10 rings from the pith — 304 pieces) or "mature" (129 pieces) depending on the location within the tree stem.

The study data clearly showed very significant effects of both density and microfibril angle on clearwood performance of the juvenile wood. In the mature wood, however, density alone was important. Overall, wood density was confirmed as the most influential parameter, affecting all classifications of wood, being easy to measure, and showing high juvenile:mature correlation.

This confirms traditional thinking and justifies the past and present efforts to document factors affecting wood density in *P. radiata* and to improve the average levels through tree breeding.

Keywords: clones; density; microfibril angle; stiffness; strength; juvenile wood; *Pinus radiata*.

INTRODUCTION

New Zealand is self-sufficient in wood products and currently also contributes around 1% of world trade. Over the past few decades there has been a policy of increasing the plantation area and intensively managing commercial forests to secure a larger share of international markets beyond the traditional regions of Australia, Japan, and Korea. Projections suggest that forest log production could increase to exceed 40 million m^3/yr within 30 years, reinforcing the desirability of securing new markets.

New Zealand *Pinus radiata* has increasingly satisfied domestic wood products requirements as diverse as structural lumber for building and construction, appearance quality lumber for furniture and joinery, treated lumber for fencing and exterior cladding, plywood, MDF, paper, and packaging. Nevertheless, the small domestic market has long been saturated and Australia is approaching self-sufficiency in many wood products. Even if traditional markets remain viable, most of the increased harvest will need to be sold into markets where buyers have access to a greater range of commercially traded wood species and non-wood materials. Possible markets are in North America, Europe, the Middle East, South-east Asia, India, and China. In all these markets, *P. radiata* will be competing with exports of familiar quality from much larger forests in North America, Russia, Scandinavia, and increasingly from "second-growth" softwood plantations.

Products manufactured from *P. radiata* will need to meet international standards of quality and performance. In this regard, wood quality is critical in determining product potential. The greatest impacts of modern forest management on wood quality have been through genetic selection and the widespread application of initial spacing, pruning, and thinning, with the resultant reduction in rotation age. The New Zealand forest estate consists predominantly of young wood that is inherently variable in material properties (Cown 1992a).

Stiffness and stability are fundamentally important wood properties which affect customer perceptions of value in both structural and appearance products. These are determined by a combination of intrinsic and in-grade features of individual pieces of lumber. However, an understanding of the fundamental factors influencing these performance characteristics is required in order to advise tree breeders on desirable selection criteria. Conventional thinking has focused on the importance of wood density and grain angle (USDA 1990), but recent work, particularly with New Zealand *P. radiata*, has also indicated a strong role for other basic wood characteristics.

There is now vigorous debate over the relative contribution of characteristics such as wood density, microfibril angle, compression wood, and spiral grain (Booker 1996;

Butterfield 1997; Cave 1968; Cave & Walker 1994; Donaldson 1995; Walker & Butterfield 1996). All are also known to be both highly variable in *P. radiata* and considered to be under strong genetic control (Sorensson *et al.* 1997). Typical patterns for wood density, spiral grain, and microfibril angle in *P. radiata* are shown in Fig. 1. Strong characteristic trends are observed. Compression wood occurs in response to external growing conditions (Cown *et al.* 1984) and cannot be represented in the same fashion.

Lumber stiffness is regarded as an important commercial characteristic but is imperfectly understood. Walford (1985) demonstrated the combined (and confounded) effects of some wood properties (wood density, ring width) on mechanical properties of *P. radiata* from pith to bark. Tsehaye & Walker (1995) suggested that selection of the stiffest 10% of *P. radiata* trees for breeding purposes would result in an overall increase of 30% in lumber stiffness.

This current study was undertaken to provide fundamental information on the impact of some additional important wood properties on strength and stiffness of standard "small clears" wood samples.

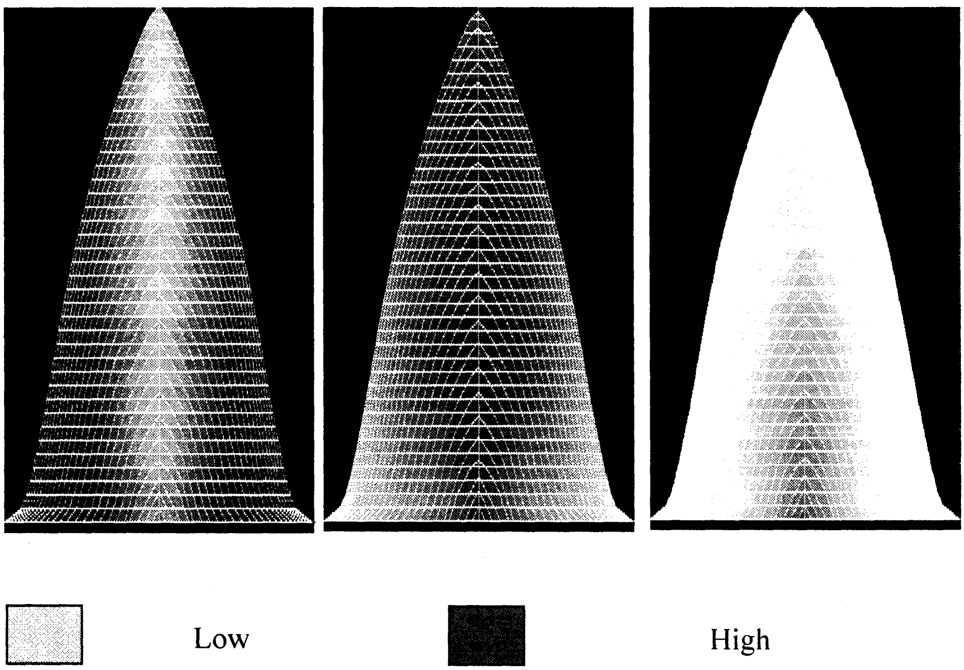

FIG. 1–Wood property patterns in 25-year-old *Pinus radiata* (a) basic wood density; (b) spiral grain; (c) microfibril angle (*from* STANDQA—Tian & Cown 1997).

MATERIALS AND METHODS

Source of Material

The wood material for this study was obtained from two Forest Research Institute clonal studies:

(1) Kaingaroa Forest Clonal Trial: Logs from ten 28-year-old clones grown in, and selected to represent, a wide range of genetic material. Material available from both juvenile and mature lumber. Two stems per clone. Uniform, conservative silviculture.

(2) Puruki Clonal Study: Logs from five, pre-selected, 23-year-old clones grown under several different spacings were processed initially into structural lumber, and "small clears" were subsequently randomly selected from both juvenile and mature wood. Five to 10 stems per clone.

The use of genetic material added a valuable dimension to the research, enabling true replication of samples (clonal ramets) and an opportunity to examine genetic influences.

Wood Samples

All logs were processed to lumber (100 × 40 mm) for grade recovery analyses (Beauregard 1996) and retained for further studies. Approximately 500 individual small samples (300 × 20 × 20 mm) were prepared from random lumber samples from the 15 clones, for static bending tests in accordance with the standard Small Clears Testing Procedures (Mack 1979), with the exception that sloping grain was included rather than avoided. All pieces were labelled according to tree number and colour-coded regarding the presence of juvenile wood (rings 1–5, 6–10, and >10 from the pith). Samples were conditioned to 12% moisture content prior to testing for static bending (stiffness) and compression parallel to the grain. On completion of the tests, each piece was assessed for the following wood properties: wood density (Dens), grain angle (GrAng—assessed on two adjacent faces), presence and position of compression wood (CW—assessed visually), and microfibril angle (MFA—Donaldson 1997). Samples predominantly from within 10 growth rings from the pith were classified as "juvenile" (n = 304), and the balance as "mature" (n = 129) (Cown 1992a).

Statistical Analyses

Stepwise multiple regression and a multi-stratum analysis of variance (calculations using Splus analysis of variance: Becker *et al.* 1988; Chambers & Hastie 1992) with tree as random effects were used to analyse the response variables (MoE and MoR) in terms of the four explanatory variables: wood density, microfibril angle, grain angle, and compression wood. It is recognised, however, that statistical associations shown by the raw correlation matrices were probably not causal. Path analyses (Wright 1960; Zhang & Zhong 1992) were used to assess evidence of causality. For the juvenile wood data the marginal probabilities of the four variables having an effect on MoE were estimated using Bayesian model selection in linear models, with all models being considered equally likely *a priori*. For this purpose a hierarchical model was used (George & McCulloch 1993; Smith & Kohn 1996). An adaptation of their Gibbs sampler (designed to improve convergence) was run for 12 000 iterations.

The juvenile and mature wood data were analysed separately, to reduce the effects of associations between variables related to the strong systematic biological within-tree trends (Cown 1992b). The multi-stratum analysis of variance splits the variation into separate strata (here between-tree and within-tree), and the variation in each stratum is analysed in terms of the explanatory variables. Additionally, both within-tree and between-tree path analyses were done. The between-tree analysis was based on tree means and gives an indication of the effects of selection of trees or clones. This analysis has the advantage of further removing the effects of within-tree patterns of variation, at the expense of a lower sample size. The within-tree analysis is more useful for a purely predictive model of wood performance but, as with any observational data, the relationships may appear to be strong but are not necessarily causal.

RESULTS

The means and variability of the raw data are shown in Fig. 2.

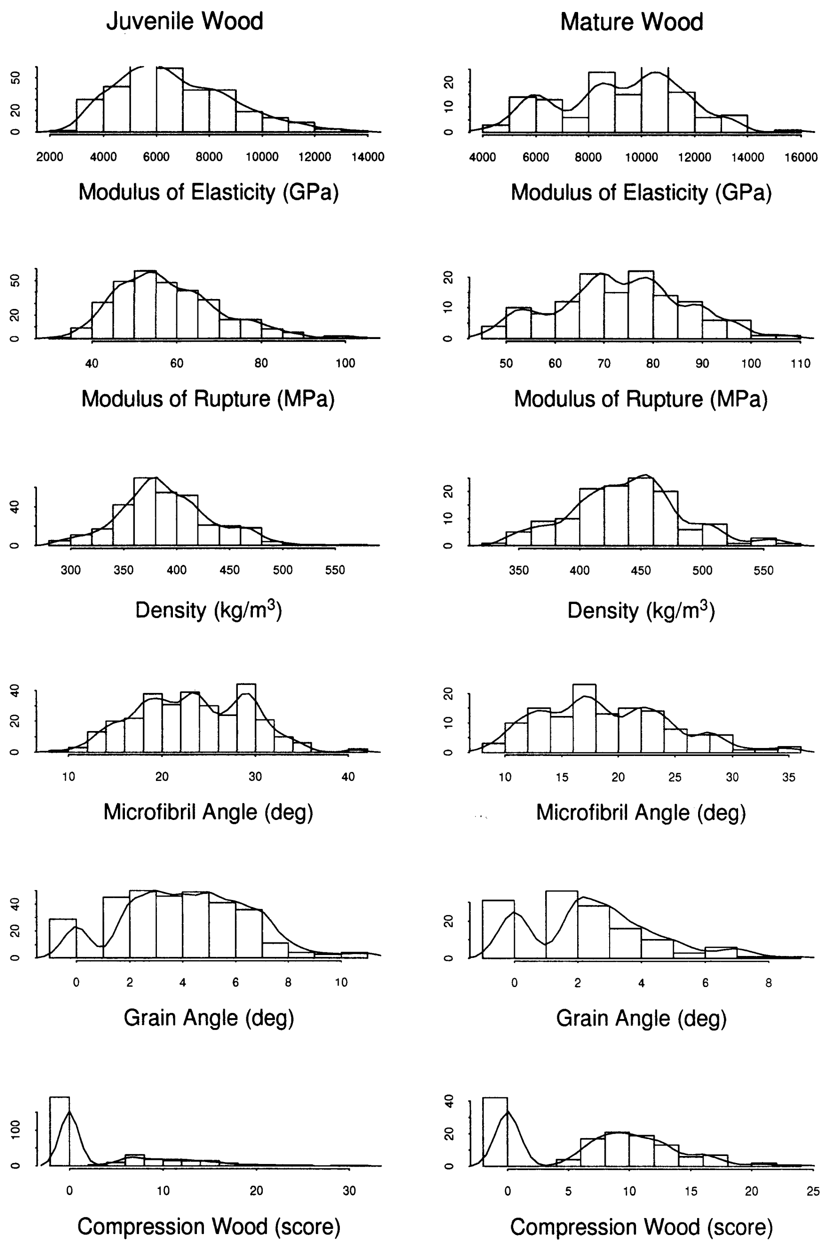

FIG. 2–Univariate distributions

Multiple Regression and Multi-stratum Analysis of Variance

The multiple regression models showed independent evidence for effects of all four variables on MoE (Table 1) and MoR (Table 2) but the predominant effects in juvenile wood were of density explaining 40% of the variance of MoE, and MFA explaining 14% of the remaining variance. Density was also the predominant effect on juvenile wood MoR, explaining 65% of the variance. In mature wood, density was by far the most highly correlated variable with mechanical properties. The column $\%SS_{seq}$ shows the percentage of sums of squares explained by terms in the order they are added in the model, and the column $\%SS_{last}$ shows the percentage of sums of squares explained by terms if they are added last in the model.

The multi-stratum analyses of variance for MoE given in Table 3 (juvenile wood) and Table 4 (mature wood) show that the effect of MFA is of importance similar to or greater than

TABLE 1–Multiple regression models for MoE (within-tree).

	Juvenile wood (RSE* = 1.4, R^2 = 59%)				Mature wood (RSE = 1.2, R^2 = 74%)			
	Coeff.	s.e.	$\%SS_{seq}$	$\%SS_{last}$	Coeff.	s.e.	$\%SS_{seq}$	$\%SS_{last}$
const	0.391	0.925	*	*	–4.195	1.296	*	*
Dens	0.026	0.002	40	24	0.037	0.003	62	43
MFA	–0.120	0.015	14	9	–0.101	0.020	8	5
GrAng	–0.173	0.036	3	3	–0.229	0.055	4	4
CW	–0.050	0.013	2	2	–0.030	0.019	<1	<1

* RSE = residual standard error

TABLE 2–Multiple regression models for MoR (within-tree).

	Juvenile wood (RSE = 6.1, R^2 = 75%)				Mature wood (RSE = 5.8, R^2 = 81%)			
	Coeff.	s.e.	$\%SS_{seq}$	$\%SS_{last}$	Coeff.	s.e.	$\%SS_{seq}$	$\%SS_{last}$
const	–6.053	4.100	*	*	–21.58	6.13	*	*
Dens	0.201	0.009	65	45	0.24	0.01	73	59
MFA	–0.375	0.065	5	3	–0.20	0.10	2	<1
GrAng	–1.129	0.160	4	4	–1.44	0.26	5	5
CW	–0.161	0.057	<1	<1	–0.20	0.09	1	1

TABLE 3–Multi-stratum analysis of variance for juvenile wood MoE.

	Df	SS	F value	Pr(F)
Between-tree error stratum				
Dens	1	280	75	<0.001
MFA	1	310	83	<0.001
GrAng	1	2	0	0.484
CW	1	16	4	0.043
Residuals	46	171		
Within-tree error stratum				
Dens	1	292	254	<0.001
MFA	1	23	20	<0.001
GrAng	1	23	20	<0.001
CW	1	10	8	0.004
Residuals	249	287		

TABLE 4–Multi-stratum analysis of variance for mature wood MoE.

	Df	SS	F value	Pr(F)
Between-tree error stratum				
Dens	1	357	148	<0.001
MFA	1	72	30	<0.001
GrAng	1	16	7	0.01
CW	1	11	5	0.04
Residuals	30	72		
Within-tree error stratum				
Dens	1	83	88	<0.001
MFA	1	7	7	0.009
GrAng	1	10	10	<0.001
CW	1	1	1	0.27
Residuals	90	86		

that of density in explaining the between-tree variation in juvenile wood MoE, but not the within-tree variation. Thus, MFA potentially has a greater role when trees are being selected for improved juvenile wood performance, than would be expected from the above regression models at the piece level. Density has the predominant effect on both the between-tree and the within-tree variation in MoE (Table 4), with a minor contribution from MFA to the between-tree variation.

Further examination showed that the high level of influence of MFA on juvenile wood MoE was detectable in the Puruki clonal trial but not in the Kaingaroa clonal trial. Similar values were obtained when the effects of microfibril angle were estimated separately for the two studies, but there was about twice as much variation in MFA between the Puruki clones as between the Kaingaroa clones, reflecting a possible genetic bias in the sampling.

Correlations Between Variables

Within- and between-tree correlations for both juvenile and mature wood are shown in Tables 5–8.

Note that correlations may not be causal—rather, some or all of the correlation between explanatory and response variables may be caused by common associations with a third variable. This occurs in trees because of the well-known pith to bark trends in wood

TABLE 5–Within-tree correlations for juvenile wood (N=304*)

	Density	MFA	Grain angle	Compression wood	MoE	MoR
Dens	1.00					
MFA	–0.24	1.00				
GrAng	–0.25	0.18	1.00			
CW	0.13	0.23	–0.05	1.00		
MoE	0.63	–0.52	–0.37	–0.15	1.00	
MoR	0.81	–0.41	–0.42	–0.02	0.91	1.00

* Minimum statistically significant correlations: 0.11, p=0.05; 0.15, p=0.01. Standard error of correlations is 0.06.

TABLE 6–Between-tree correlations for juvenile wood (N=51*)

	Density	MFA	Grain angle	Compression wood	MoE	MoR
Dens	1.00					
MFA	–0.22	1.00				
GrAng	–0.42	0.35	1.00			
CW	–0.00	0.52	0.04	1.00		
MoE	0.58	–0.76	–0.40	–0.42	1.00	
MoR	0.85	–0.54	–0.53	–0.24	0.89	1.00

* Minimum statistically significant correlations: 0.28, p=0.05; 0.36, p=0.01. Standard error of correlations is 0.14.

TABLE 7–Within-tree correlations for mature wood(N= 129*)

	Density	MFA	Grain angle	Compression wood	MoE	MoR
Dens	1.00					
MFA	–0.29	1.00				
GrAng	–0.12	0.20	1.00			
CW	0.08	0.10	–0.06	1.00		
MoE	0.78	–0.49	–0.33	–0.04	1.00	
MoR	0.86	–0.37	–0.33	–0.02	0.92	1.00

* Minimum statistically significant correlations: 0.17 (p=0.05), 0.23 (p=0.01). Standard error of correlations is 0.09.

TABLE 8–Between-tree correlations for mature wood (N=35*)

	Density	MFA	Grain angle	Compression wood	MoE	MoR
Dens	1.00					
MFA	–0.31	1.00				
GrAng	–0.34	0.23	1.00			
CW	0.35	–0.05	–0.08	1.00		
MoE	0.80	–0.55	–0.43	0.18	1.00	
MoR	0.91	–0.45	–0.42	0.24	0.95	1.00

* Minimum statistically significant correlations: 0.33 (p=0.05), 0.43 (p=0.01). Standard error of correlations is 0.17.

properties noted earlier. Note also the lower correlations between trees. If sampling error is ignored, and there are no causal variables other than those considered here, the causal part of the correlations will be less than or equal to these raw correlations but greater than or equal to the direct path coefficients below.

Path Analyses

The direct path coefficients derived for the "all-samples" and "between-tree" analyses are shown in Tables 9 and 10.

TABLE 9–Path coefficients for juvenile wood.

	All-samples (N=304)*				Between-tree (N=51)†			
	Density	MFA	Grain angle	Comp. wood	Density	MFA	Grain angle	Comp. wood
MoE	0.53	–0.33	–0.18	–0.15	0.45	–0.60	–0.01	–0.11
MoR	0.72	–0.18	–0.21	–0.09	0.74	–0.30	–0.11	–0.08

* Minimum statistically significant correlations: 0.11 (p=0.05), 0.15 (p=0.01). Standard error of correlations is 0.06.

† Minimum statistically significant correlations: 0.28 (p=0.05), 0.36 (p=0.01). Standard error of correlations is 0.14.

TABLE 10–Path coefficients for mature wood.

	Within-tree (N=129)*				Between-tree (N=51)†			
	Density	MFA	Grain angle	Comp. wood	Density	MFA	Grain angle	Comp. wood
MoE	0.70	–0.25	–0.20	–0.08	0.69	–0.30	–0.13	–0.08
MoR	0.81	–0.09	–0.23	–0.09	0.84	–0.17	–0.10	–0.07

* Minimum statistically significant correlations: 0.17 (p=0.05), 0.23 (p=0.01). Standard error of correlations is 0.09.

† Minimum statistically significant correlations: 0.33 (p=0.05), 0.43 (p=0.01). Standard error of correlations is 0.17.

Overall, it is clear that the effects of wood density and microfibril angle on MoE were the strongest, with density having more impact within stems, while MFA may have had slightly more effect on MoE between stems. Density had the greatest effect on MOR, followed by MFA and spiral grain, with similar small effects within trees. MFA also appeared to have a greater effect on between-tree variation in MoR than on within-tree variation.

Bayesian Model Selection

Bayesian model selection estimated using Gibbs sampling was used to assess the evidence for effects of the explanatory variables on specific modulus (MoE/density) in juvenile wood. The estimated marginal probabilities were as shown in Table 11.

TABLE 11–Estimated marginal probabilities for effects on specific modulus of juvenile wood.

	Density	MFA	Grain angle	Comp. wood
probability	0.18	1.0	0.89	0.06

Thus there is strong evidence for an effect of MFA, some evidence for an effect of GrAng (9:1 odds in favour), and evidence against an additional effect of density (5:1 odds against) or compression wood (15:1 odds against).

This is consistent with the logical expectation that MoE should increase linearly with density (all other parameters held constant), and hence have no effect on specific modulus.

DISCUSSION AND CONCLUSIONS

A number of authors (Cave & Walker 1994; Walker & Butterfield 1996) have argued that MFA has a predominant effect on MoE in wood. These arguments are usually based heavily on theory, and on the fact that MoE appears to increase non-linearly when plotted against wood density alone. The Bayesian model analysis of specific modulus for juvenile wood showed no evidence of a super-linear effect of density on MoE. However, the results showed that, in the juvenile wood portion of the stem, wood density and microfibril angle seem to contribute equally in the overall data set. The data presented here are not completely definitive because of the finite number of genotypes (clones), but the study provided robust statistical evidence for a causal effect of both density and MFA on MoE in the juvenile clearwood of *Pinus radiata*. Conversely, in the mature wood, density had an overwhelming effect. Interestingly, at the between-tree level, MFA showed up as a significant variable, perhaps because juvenile wood samples comprised 70% of the overall material.

The impact of grain deviation was not strong in this data set.

The effect of compression wood is less easily documented because of the subjective measurement method (visual) and the association with microfibril angle. There was evidence in the auto-correlations of a relationship both within and between trees in the juvenile wood and, while the statistical evidence of a significant effect on stiffness and strength in this study is weak, there are certainly observational indications of a negative effect on wood stability.

For structural lumber recovery from a whole tree stem, wood density must be considered the most important basic wood characteristic for a number of reasons. The effect of MFA overall on the value of machine stress grades obtained from a stem may not be great because of the relatively small amount of wood with high MFA (predominantly near the base of the stem) and because this wood also has the lowest wood density and a high proportion of knots and spiral grain. Wood density contributes very significantly to both juvenile and mature wood clearwood characteristics and has also been demonstrated to be important in influencing the in-grade mechanical properties of structural *P. radiata* lumber (Walford 1984).

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REFERENCES

BEAUREGARD, R. 1996: Sawing strategies in New Zealand. Paper presented at Session 10: "Matching Sawmill Resources to Available Technology", Annual meeting of the US Forest Products Society, 23–26 June, Minneapolis, Minnesota, United States.

BECKER, R.A.; CHAMBERS, J.M.; WILKS, A.R. 1988: "The New S Language, a Programming Environment for Data Analysis and Graphics". Wadsworth and Brooks/Cole Advanced Books and Software, Pacific Grove, California.

BOOKER, R.E. 1996: The reasons for the microfibril orientations in the tracheid cell walls of trees. Pp.273–282 *in* Donaldson, L.A.; Singh, A.P.; Butterfield, B.G.; Whitehouse, L.J. (Ed.) "Recent Advances in Wood Anatomy". New Zealand Forest Research Institute, Rotorua. 429 p.

BUTTERFIELD, B.G. (Ed.) 1997: "Microfibril Angle in Wood". Proceedings of IAWA/IUFRO International Workshop on the Significance of Microfibril Angle to Wood Quality. Westport, New Zealand, November. 410 p.

CAVE, I.D. 1968: The anisotropic elasticity of the plant cell wall. *Wood Science & Technology 2(4)*: 268–278.

CAVE, I.D.; WALKER, J.C.F. 1994: Stiffness of wood in fast-grown plantation softwoods: The influence of microfibril angle. *Forest Products Journal 44(5)*: 43–48.

CHAMBERS, J.; HASTIE, T. 1992: "Statistical Models in S". Wadsworth and Brooks/Cole Advanced Books and Software, Pacific Grove, California.

COWN, D.J. 1992a: Corewood (juvenile wood) in *Pinus radiata*—Should we be concerned? *New Zealand Journal of Forestry Science 22(1)*: 87–95.

———1992b: New Zealand radiata pine and Douglas fir: Suitability for processing. *New Zealand Ministry of Forestry, Forest Research Institute, FRI Bulletin No.168*. 74 p.

COWN, D.J.; McCONCHIE, D.L.; TRELOAR, C. 1984: Timber recovery from pruned *Pinus radiata* butt logs at Mangatu: Effect of log sweep. *New Zealand Journal of Forestry Science 14(1)*: 109–123.

DONALDSON, L.A. 1995: Microfibril angle: Its influence on wood properties and prospect for improvement in radiata pine. Pp. 20–25 *in* Klitscher, K.R.; Cown, D.J.; Donaldson, L.A. (Ed.) "Wood Quality Workshop", Rotorua, 15 November.

———1997: Rapid screening of microfibril angle. Pp.13–14 *in* Ridoutt, B.G. (Ed.) "Managing Variability in Resource Quality". *New Zealand Forest Research Institute, FRI Bulletin No. 202.*

GEORGE, E.I.; McCULLOCH, R.E. 1993: Variable selection via Gibbs sampling. *Journal of the American Statistical Association 88*: 881–889.

MACK, J.J. 1979: Australian methods for mechanically testing small clear specimens of timber. *CSIRO, Division of Building Research, Technical Paper No. 31*. 19 p.

SMITH, M.; KOHN, R. 1996: Nonparametric regression using Bayesian variable selection. *Journal of Econometrics 75(2)*: 317–343.

SORENSSON, C.T.; COWN, D.J.; RIDOUTT, B.G.; TIAN, X. 1997: The significance of wood quality in tree breeding: A case study of radiata pine in New Zealand. Paper presented at Canadian Tree Improvement Association/IUFRO Conference, Quebec City, Canada, August.

TIAN, X.; COWN, D.J. 1997: STANDQUA: A modelling tool to predict the interactions of site and silviculture on wood properties and log quality in New Zealand. Society of American Foresters, 7th Symposium on Systems Analysis in Forest Resources, Traverse City, Michigan, May. 8 p.

TSEHAYE, A.; WALKER, J.C.F. 1995: Stiffness and tensile strength variation within and between radiata pine trees. *Journal of the Institute of Wood Science 13(5)*: 513–518.

USDA 1990: Wood handbook: Wood as an engineering material. *USDA Forest Service, Agriculture Handbook 72.*

WALFORD, G.B. 1984: In-grade bending strength of radiata pine. *In* Proceedings of the Pacific Timber Engineering Conference, Auckland, New Zealand, May, S61-70.

———1985: The mechanical properties of New Zealand grown radiata pine for export to Australia. *New Zealand Forest Service, Forest Research Institute, FRI Bulletin No. 93.*

WALKER, J.C.F.; BUTTERFIELD, B.G. 1996: The importance of microfibril angle for processing industries. *New Zealand Forestry 40(4)*: 34–40.

WRIGHT, S. 1960: Path coefficients and path regressions: alternative or complementary concepts? *Biometrics 16*: 189–202.

ZHANG, S.Y.; ZHONG, Y. 1992: Structure-property relationship of wood in East-Liaoning oak. *Wood Science and Technology 26*: 139–149.