VARIATION IN MICROFIBRIL ANGLE AMONG THREE GENETIC GROUPS OF *PINUS RADIATA* TREES

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ABSTRACT

Microfibril angle at breast height and at 18 m was assessed for three genetically distinct groups of *Pinus radiata* D.Don trees. The three groups consisted of five trees of undefined parentage, five trees of open-pollinated NZ850-55, and five trees of NZ850-55 × Guadalupe provenance *P. radiata*. Microfibril angle within the corewood at breast height was consistently lower for the two NZ850-55 progeny groups than for the corewood of the control trees, while outerwood values were comparable. Angles at 18 m height were similar to those at breast height for the two NZ850-55 progeny groups but were significantly lower in the control trees. These differences have implications for wood and paper properties.

Keywords: microfibril angle; wood quality; *Pinus radiata*.

INTRODUCTION

In the past, the New Zealand *P. radiata* tree breeding programme has concentrated on selection for such attributes as growth rate, internode length, and crown form. More recently, there has been some interest in the potential for selection based on other criteria, especially wood properties.

Results from mechanical pulping trials carried out at the New Zealand Forest Research Institute have produced evidence of genetic variation in pulping qualities (Corson *et al.* 1989). This study compared a group of genetically select *P. radiata* trees with a genetically undefined group representing standard *P. radiata*, and several trees of New Zealand-grown *Picea abies* (L.) Karst. and *Picea sitchensis* (Bong.) Carr. The genetically select *Pinus radiata*, progeny from a single tree of the "850" series family known as NZ850-55 or Clone 55, showed a lower energy consumption for pulping to a specified freeness, than standard *P. radiata*. Light-scattering coefficients were also superior in pulps made from NZ850-55 progeny (Corson *et al.* 1991). This was the first direct observation of significant variation in pulping qualities for *P. radiata*, and has generated considerable interest in the pulp and paper industry and among tree breeders.

As part of an investigation into the genetics of wood properties and in an attempt to explain the unusual properties of the wood from NZ850-55 progeny, a detailed analysis of the microscopic wood properties of such trees was undertaken. A recent comparison between lignin distribution in control-pollinated progeny of NZ850-55 and that in standard *P. radiata* revealed a consistent reduction in the lignification of the middle lamella in these trees (Donaldson in press). While this reduced lignification may not be sufficient to account for the reduced energy consumption during mechanical pulping shown by this group of trees, other differences in cell wall structure or composition are likely to be involved.

Microfibril angle, the angle between cellulose microfibrils in the cell wall and the cell axis, has an important influence on wood properties, especially longitudinal and tangential shrinkage (Harris & Meylan 1965), and Young's modulus (Cave 1968, 1969). Using multivariate analysis, Wimmer (1992) found that microfibril angle is an important determinant of mechanical properties in clearwood of pine when the influence of specific gravity is excluded. Microfibril angle varies from pith to bark with the largest angles occurring in the first 5–10 growth rings from the pith (Phillips 1941; Preston 1948, 1949; Wardrop & Dadswell 1950; Pillow *et al.* 1953; Echols 1955; Manwiller 1972; Erickson & Arima 1974; Bendtsen & Senft 1986; Pedini 1992; Donaldson 1992). The variation of microfibril angle with height has not been extensively investigated but studies suggest that microfibril angle declines with height in the stem (Pillow 1953; Manwiller 1972; Pedini 1992; Donaldson 1992).

Microfibril angle also has a significant effect on paper properties (Kellogg *et al.* 1975). Low (steeper) microfibril angles are associated with high tensile strength in paper while high microfibril angles are associated with larger stretch and tear indices (Watson & Dadswell 1964). Mark (1967) showed that fibres with high microfibril angles tend to stretch more before failure in longitudinal tension than those with low microfibril angles which have higher tensile strength.

Microfibril angle is known to be inversely related to tracheid length, with longer tracheids having smaller angles (Preston 1948, 1949; Preston & Wardrop 1949; Wardrop & Dadswell 1950; Wardrop 1951; Echols 1955). The relationship between microfibril angle and tracheid length is thought to reflect the strains imposed on cells at their time of differentiation (Boyd 1985).

Harris (1977) examined the variation of microfibril angle in relation to visual compression wood grade in *P. radiata* but found no significant differences between compression wood and opposite wood within the same growth ring. Other studies have found that compression wood often has higher microfibril angles than opposite wood from the same stem (Wardrop & Dadswell 1950; Park *et al.* 1980).

As part of a detailed investigation of the variation in cell wall properties among genetically different groups of *P. radiata*, this report examines the variation in microfibril angle among three such groups.

MATERIALS AND METHODS

Discs were collected at breast height and at 18 m height from five trees of genetically undefined *P. radiata* (1013) (one tree per genotype) growing in Cpt 1013 of Kaingaroa

Forest, planted in 1965. Samples of earlywood were taken from every fifth growth ring at breast height, starting at the outermost ring on each disc. The ring adjacent to the pith was also sampled. This sampling strategy was used to allow comparison of wood produced during the same growing season as part of another study. Discs collected at 18 m were sampled at rings 1, 5, and 10 from the pith.

In addition, discs were collected at breast height and at 18 m from five NZ850-55 open-pollinated crosses (OP) (one tree per genotype) and five NZ850-55 Guadalupe crosses (GUAD) (one tree per genotype) growing in Cpt 1350 of Kaingaroa Forest, planted in 1971. These trees were selected on the basis of wood density, determined from previous increment core sampling, in order to carry out pulping trials on wood of predetermined density. The OP trees had a mean density of 370 kg/m^3 while the GUAD trees had a mean density of 430 kg/m^3, equivalent to that of the 1013 trees. The Guadalupe provenance originates from the Mexican island of Guadalupe and is a slow-growing, higher wood density variety of *P. radiata*.

Pieces of earlywood were macerated in a 50:50 mixture of glacial acetic acid and hydrogen peroxide (130 vol.) at 90°C for 4 hours. Microfibril angle was measured on 25 tracheids for each growth ring using the technique described by Donaldson (1991).

Because the three groups of trees were of different ages, sampling from bark to pith on the breast height discs did not produce coincident growth rings with respect to cambial age (distance from the pith). In order to allow a comparison on the basis of cambial age, curvilinear (quadratic) regressions were calculated for each tree using growth ring number from the pith as the determinate variable. These regressions were then used to calculate predicted microfibril angle for the first 20 growth rings from the pith for each tree. Subsequent comparisons were based on these predicted values.

Growth increment was measured for each growth ring at breast height and these values were used to calculate volume-weighted microfibril angle for the corewood and outerwood of the butt log, using predicted microfibril angle at breast height. Corewood was classified as the first 10 rings from the pith. Volume-weighted values for top logs and whole trees were calculated using the prediction equations given by Donaldson (1992) for the 1013 trees, while breast height values were used for the other trees. Predicted values at 18 m were compared to actual values in order to assess the applicability of prediction equations to an independent sample of trees. Growth increment at breast height was used for all volume-weighting calculations (Donaldson 1992).

RESULTS AND DISCUSSION

The regression equations used to calculate predicted microfibril angle for each tree are given in Table 1 and the average predicted values for each group of trees plotted against cambial age are given in Fig. 1. The OP and GUAD trees had slightly lower predicted microfibril angles within the corewood than the 1013 trees, with differences of up to 8° in some growth rings. In the outerwood, values converged by ring 20.

An analysis of variance for these data (Table 2) indicated highly significant incremental variation in predicted microfibril angle but no significant variation among groups at the 0.05 probability level. However, the size of the groups MS in Table 2 suggests that there may be

TABLE 1–Regression equations for predicted microfibril angle at breast height for individual trees

Group	Prediction equation	r^2
1013		
1	$Y_p = 39.60 - 3.23X + 0.10X^2$	88
2	$Y_p = 48.28 - 3.49X + 0.10X^2$	98
3	$Y_p = 54.10 - 4.19X + 0.12X^2$	99
4	$Y_p = 41.53 - 0.78X - 0.01X^2$	95
5	$Y_p = 52.44 - 3.44X + 0.08X^2$	98
OP		
1	$Y_p = 46.64 - 2.19X + 0.02X^2$	98
2	$Y_p = 39.63 - 3.67X + 0.13X^2$	66
3	$Y_p = 50.73 - 4.98X + 0.17X^2$	99
4	$Y_p = 57.22 - 4.59X + 0.13X^2$	99
5	$Y_p = 36.77 - 3.74X + 0.15X^2$	83
GUAD		
1	$Y_p = 49.57 - 4.94X + 0.16X^2$	99
2	$Y_p = 32.04 - 2.89X + 0.11X^2$	97
3	$Y_p = 50.44 - 3.94X + 0.10X^2$	99
4	$Y_p = 35.48 - 3.03X + 0.11X^2$	78
5	$Y_p = 39.18 - 3.52X + 0.14X^2$	94

Y_p = predicted microfibril angle
X = cambial age

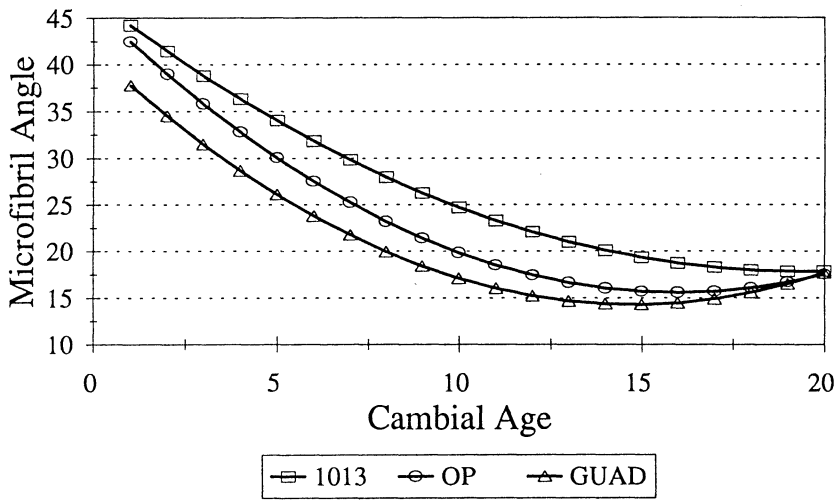

FIG. 1–Variation in predicted microfibril angle at breast height with cambial age among three genetic groups of *P. radiata*

some difference among groups ($p = 0.072$). A larger sample size may have more clearly defined the difference among groups. The absence of a significant interaction between cambial age and groups indicated that all three groups of trees had similar pith to bark trends in predicted microfibril angle.

TABLE 2–Analysis of variance for predicted microfibril angle among groups, trees, and growth rings at breast height

Source	df	MS	F	p
Groups	2	963.41	3.30	0.072
Trees within groups	12	291.88	–	–
Rings	17	1027.18	113.87	0.000
Group × ring	34	4.74	0.55	0.978
Residual	136	8.64		

Groups = fixed
Rings = fixed
Trees = random
The trees within groups MS is based on the pooled sums of squares for trees and the group × tree interaction

Because the two genetically select groups share a common parent, it might be expected that variation among trees would be reduced in these two groups compared to the non-select group. That this did not happen suggests that differences between the select and the non-select groups originated from the non-NZ850-55 parents. A difference in some environmental factor cannot be discounted as the non-select trees were growing at a different, although comparable, location.

Since the over-all effect of microfibril angle on wood properties will depend on the relative proportions of different growth rings, it was necessary to weight microfibril angle for each growth ring in proportion to the volume of that ring. A comparison of growth increment among the three groups is given in Fig. 2 and cumulative wood volume percentage in Fig. 3. The OP and GUAD groups had more corewood than the 1013 group of trees (Fig. 2 and 3). An analysis of variance for growth increment among the three groups indicated no significant difference among groups (Table 3). However, there was a significant interaction between groups and rings, reflecting differences in corewood growth increment. There was

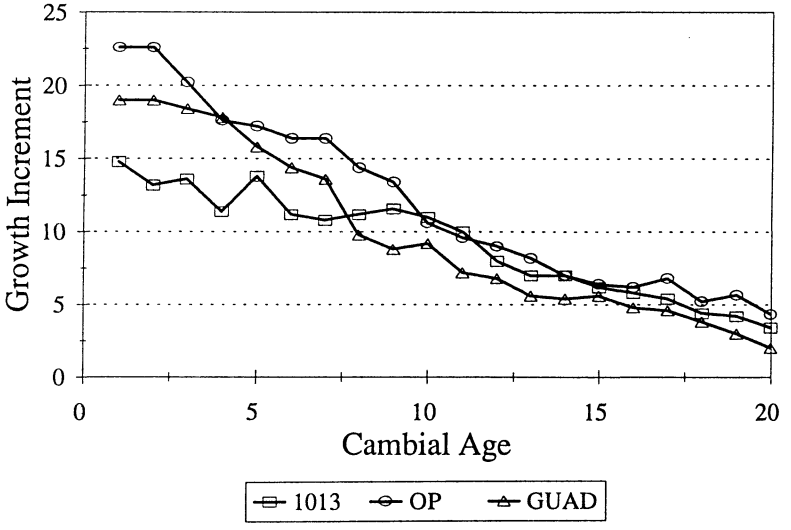

FIG. 2–Variation in growth increment among three genetic groups of *P. radiata*

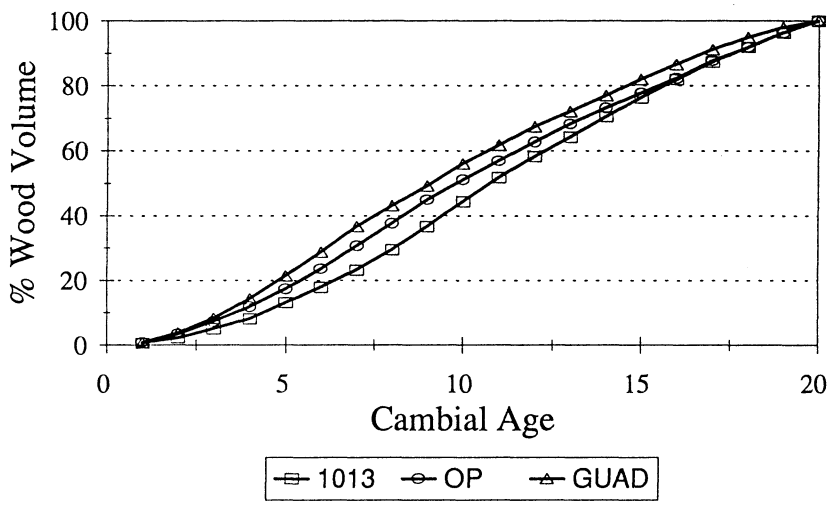

FIG. 3–Variation in cumulative wood volume percentage among three genetic groups of *P. radiata*

TABLE 3–Analysis of variance for growth increment among groups, trees, and growth rings

Source	df	MS	F	p
Groups	2	214.90	2.40	0.133
Trees within groups	12	89.71	–	–
Rings	17	344.14	59.42	0.000
Group × ring	34	16.94	2.91	0.000
Residual	136	5.82		

also significant variation among trees within groups. The corewood region at breast height represented 44% of butt log volume in the 1013 group while values for the OP and GUAD groups were 51% and 56% respectively.

From an earlier study (Donaldson 1992) it was found that mean microfibril angle at breast height could be related to mean microfibril angle at other heights for groups of trees. Prediction equations were developed to allow calculation of predicted mean microfibril angle at butt, 7, 12, 18, 23, and 30 m height. Observed and predicted mean microfibril angles at 18 m are given in Fig. 4 for rings 1, 5, and 10 among the three groups of trees examined in the present study. While predicted and observed values were in close agreement for the 1013 group (the same trees used to develop the prediction equations—Donaldson 1992), values for the other two groups showed quite large differences between predicted and actual values. Within the 1013 group, trees showed an average decline in microfibril angle with height above breast height, with slight increases near the top of the stem. For both the OP and GUAD groups, microfibril angles seemed to remain more or less constant above breast height, based on sampling at 18 m. There were, therefore, three components to the variation among the three groups examined in this study. Predicted microfibril angle at breast height

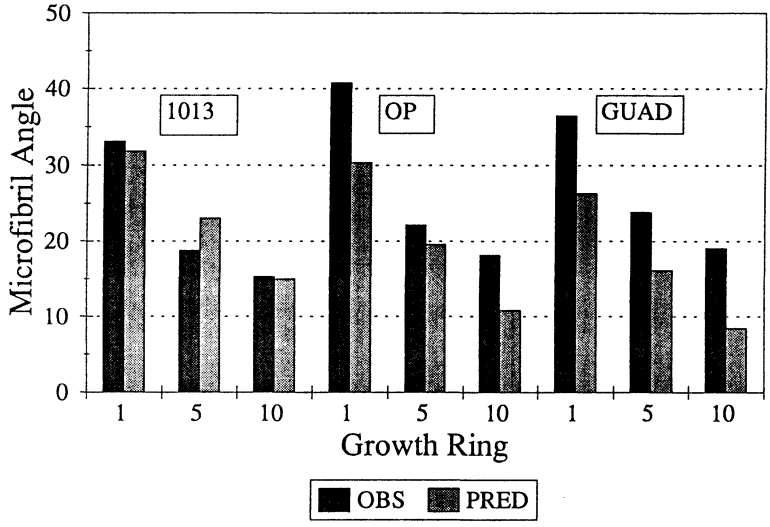

FIG. 4–Variation in observed and predicted microfibril angle at 18 m height among three genetic groups of *P. radiata*

was lower in the corewood of the OP and GUAD groups, the amount of corewood was greater in these trees, and microfibril angles above breast height did not follow the pattern of reducing angles observed in the 1013 group.

Analysis of variance for microfibril angle at 18 m is given in Table 4. Because the data at 18 m include replication, it is possible to examine several interactions that could not be tested in Table 2. The variation among groups was not significant, but there were significant interactions between groups and trees, trees and rings, and groups, trees, and rings.

Volume-weighted microfibril angles among the three groups (Fig. 5) incorporated the variation in growth rate and changes in microfibril angle with height described above. The values for the top log and whole stem were based on predicted microfibril angles for the 1013 group but breast height values were used for the OP and GUAD groups, assuming that microfibril angle remains constant above breast height in these trees. It is worth noting that, while butt log values were lower in the OP and GUAD groups, top log values were predicted to be much higher in these trees. Whole-tree values for the 1013 and GUAD groups were

TABLE 4–Analysis of variance for microfibril angle at 18 m height

Source	df	MS	F	p
Groups	2	2363.13	1.50	0.262
Trees within groups	12	1575.09	21.98	0.000
Trees	4	1713.47	23.91	0.000
Rings	2	38649.18	147.20	0.000
Groups × trees	8	1505.90	21.02	0.000
Groups × rings	4	386.25	0.50	0.740
Trees × rings	8	262.55	3.66	0.000
Groups × trees × rings	16	771.52	10.77	0.000
Residual	1080	71.66		

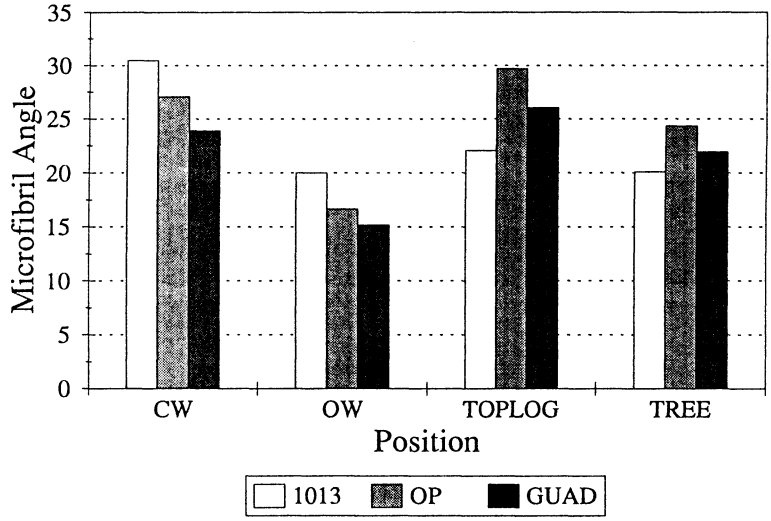

FIG. 5–Variation in volume-weighted microfibril angle for corewood and outerwood of the butt log, and for the top log and whole tree, among three genetic groups of *P. radiata*

similar while the OP group had a slightly higher average value. This analysis assumed that trees in each group were of the same age (20 rings) and showed the same height growth (30 m).

The large differences in microfibril angle variation with height among the three groups examined may be related to differences in height growth among the three groups of trees. If both the OP and GUAD trees were shorter than the 1013 trees at an equivalent age, then the physiological heights would also have been less. The 1013 trees examined in detail by Donaldson (1992) showed a decline in microfibril angle with height within the first 7 m, followed by a gradual increase above 18 m. This pattern could produce higher microfibril angles at equivalent heights in shorter trees. Further examination of the variation in microfibril angle with height in a large number of trees is needed before any accurate method for predicting variation with height can be developed. It may be that the differences observed among these three groups are related to their genotype and that the model developed for variation with height in the 1013 trees may be applicable to trees other than NZ850-55 progeny. The presence of compression wood may also have influenced the variation in microfibril angle with height.

Other authors have described a decline in microfibril angle with height in several softwood species. Pillow *et al.* (1953) measured microfibril angle in three trees of *Pinus taeda* L. at breast height and at 9–12 m where values were significantly lower. Manwiller (1972) also found a decline in microfibril angle with height in *Pinus glabra* Walter. Pedini (1992) observed a decline in microfibril angle within a ring with height in *Picea sitchensis*. These results suggest that the lack of an apparent decline in microfibril angle with height in NZ850-55 progeny may be an abnormal characteristic of this genotype.

Because the differences in microfibril angle between the groups of trees examined in this study are small compared to the variation that occurs among growth rings or among trees

(Donaldson 1992), it is unlikely that microfibril angle is a significant factor in determining energy consumption during mechanical pulping. However, within-tree variation may mean that paper and solid-wood properties are significantly affected, depending on which part of the stem is being utilised. Lower microfibril angles in the butt logs of NZ850-55 progeny may produce pulp fibres that are significantly stiffer than those of standard *Pinus radiata*, while the opposite may happen in pulp fibres produced from top logs (Watson & Dadswell 1964; Mark 1967; Kellogg *et al.* 1975). Microfibril angles in pulp fibres made from slabwood are likely to be similar in all three groups.

The mechanical strength properties of wood from NZ850-55 progeny with higher whole-tree microfibril angle values, especially in the open-pollinated trees examined here, would be expected to be lower than for standard *P. radiata* (Cave 1968, 1969). Mechanical strength for wood from the butt log may be improved owing to lower microfibril angles in this part of the stem, especially in the GUAD trees where higher average density would also contribute to improved strength.

Microfibril angle is strongly correlated with tracheid length, longer tracheids having lower microfibril angles (Preston 1948, 1949; Preston & Wardrop 1949; Wardrop & Dadswell 1950; Echols 1955). Tracheids in NZ850-55 progeny are significantly longer than average for *P. radiata* at breast height (G.D.Young pers. comm.), and this agrees well with the lower microfibril angles observed in the present study. This observation is important because it confirms that the observed relationship between tracheid length and microfibril angle is not due entirely to the common covariance of these two factors with cambial age.

CONCLUSIONS

Microfibril angle varied among the three groups of trees examined, with over-all trends indicating lower microfibril angles in the butt logs of NZ850-55 progeny, but with higher microfibril angles for top logs and whole trees. Predicted variation with height did not agree with measured values at 18 m height in the NZ850-55 progeny, suggesting that microfibril angle may not decline above breast height as it does in standard *P. radiata*.

For individual genotypes (individual trees) differences in microfibril angle may be large enough to affect wood and paper properties significantly. However, because of the large within- and between-tree variations in microfibril angles observed, it seems unlikely that differences in microfibril angle could explain differences in energy requirements for mechanical pulping in NZ850-55 progeny. A comparison of multiple trees of the same genotype (clones) growing on adjacent sites is required to confirm that microfibril angle is influenced by genotype.

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