

The importance of microfibril angle for the processing industries

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Abstract

Conventional thinking about wood quality centres on the primacy of density. This review observes that many wood characteristics are age related and co-vary with one another (density, tracheid length, microfibril angle, lignin content etc.); indeed correlations between and within properties and characteristics can be high. Selection of any favourable characteristic has benefits for a number of wood properties, with the overall gain depending on the characteristic sought for improvement and its effect on all wood properties. In the case of *Pinus radiata* the intrinsic characteristic whose improvement is likely to yield the greatest economic benefits is the microfibril angle.

Introduction

Any consideration of individual wood characteristics must take account of the intended end use, since many characteristics have claims on the tree breeder's attention. An hierarchical approach needs to examine:

1. What is wanted: the product(s) to be improved and their Achilles heel, e.g. kraft pulp (poor tear), furniture (low hardness), structural timber (poor stiffness) etc.
2. Where to look: corewood or outerwood; butt or top log.
3. What to look for: microfibril angle or density, tracheid length, lignin content, spiral grain.
4. When to look: in the nursery or later.

What is wanted

Wood technologists spend much time developing strategies to overcome deficiencies in timber. However, some problems are more intransigent than others. Thus with kraft pulp tensile and burst indices can be improved by beating, whereas tear strength responds only to light beating and thereafter declines. In developing approaches to tree improvement it may be useful to classify properties into those that can be manipulated readily during processing (tensile and burst) and those which cannot (tear). There may be grounds for focusing a breeding programme on those properties that cannot be manipulated during processing even though other properties appear to offer a more obvious financial return.

Where to look: corewood or outerwood?

Assuming the first ten rings define corewood, the proportion of corewood in a 25-year-old tree (Figure 1) increases from the butt to the top log (Cown, 1992a) and equates very closely to a 50:50 split for the whole merchantable volume.

It is acknowledged that the most valuable timber is in the outerwood, which in turn is often taken to imply that efforts in tree improvement should concentrate on that zone: indeed a good case for concentrating on outerwood properties applies where long rotations are contemplated. Further, in the case of wood density we find ... more variation in outerwood than in corewood densities (Figure 2a), and since the environmental influences (cli-

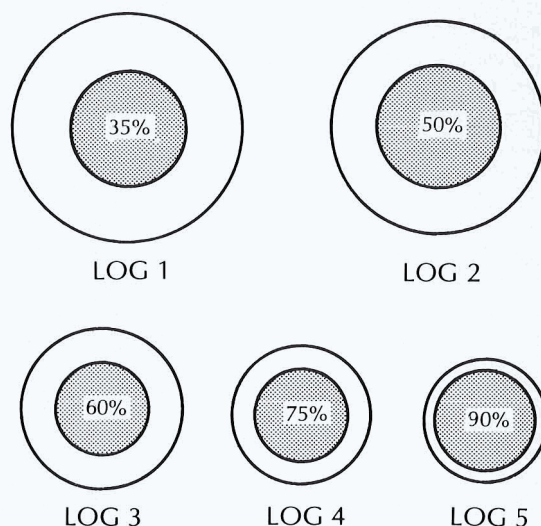


Figure 1. Corewood in a 25-year-old tree (adapted from Cown, 1992a).

mate, site) can be assumed to remain within well-defined bounds throughout the life of the tree crops, it appears that their contribution to wood formation becomes more marked with tree age (Cown et al., 1991).

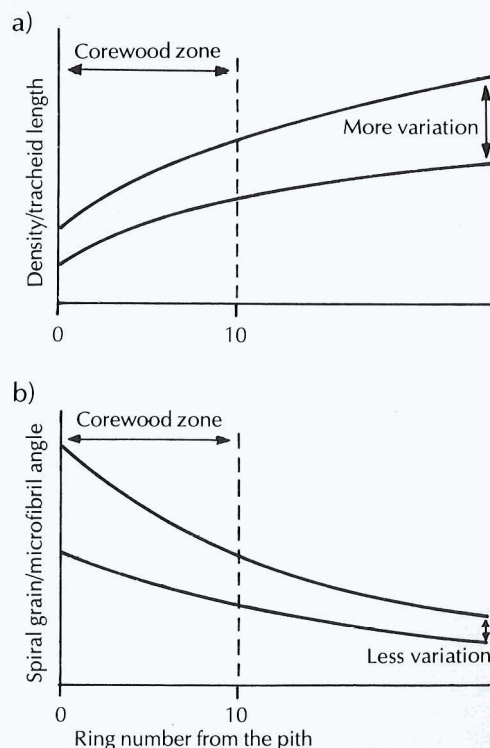


Figure 2. (a) characteristics which show more variation in outerwood, (b) characteristics which show more variation in corewood.

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... Variation in corewood density was associated with about 50% of the variation ($r = 0.72$) of the outerwood density. Hence, early density assessments are not particularly useful for predicting mature wood levels (Cown *et al.*, 1991). Thus, by concentrating on outerwood one has the potential to capture a large increase in density (more variation) while also cashing in on 50% of the more restricted increase in density (less variation) in the corewood.

However, ... This possibility raises, in turn, the question as to whether selection for corewood density (as in these five-year-old trees) has much relevance for future "intermediate" or "outerwood" production. It is true that density of corewood is poorly correlated with density of outerwood ... but this purely statistical assessment can be misleading. Although wood density always increases from the pith outwards, the gradient of this increase is very variable ... (Harris *et al.*, 1976).

... A good case can be made for selecting high wood density in corewood: since no instance has been recorded of any behaviour other than increasing density from the pith outwards, high-density corewood would increase the mean density and effectively reduce within-stem variability. For all end uses, including mechanical pulping, the elimination of very low-density corewood would be advantageous. In particular, it could have the important effect of improving basic stresses for the species, since these are determined by the lowest 1% of results from strength tests on clear timber (Harris *et al.*, 1976).

Here, the argument is made for targeting corewood density rather than outerwood density despite its smaller variability: a 5% potential improvement has been mentioned as against a 10% improvement when selecting on the basis of outerwood density (Harris & Cown, 1991). If the "dream" target is to be 20-year-old sawlogs this argument becomes more insistent as the tree will be mostly corewood, with some intermediate wood and no mature wood. The same argument holds for tracheid length, with the balance favouring selection in the corewood as the rotation age is reduced (Figure 2a). The ranking of families according to the value of their outerwood characteristics will change somewhat as the age of clear felling declines.

With spiral grain and microfibril angle there is more variation in corewood than in outerwood characteristics (Figure 2b), and the greatest benefit would undoubtedly be achieved by improving corewood regardless of the rotation age.

All studies of corewood list its undesirable qualities (Senft *et al.*, 1985): low basic density, high moisture content, above average compression wood, higher longitudinal shrinkage, low cellulose content, short fibres with low tear. Desirable features of corewood in solid wood processing are that it is more even-textured, having less within-ring variability with both less and lower-density latewood (less contrast between earlywood and latewood), and its lower transverse shrinkage (being of lower density). In paper the collapse of the thin-walled fibres gives good printability.

If corewood properties are so poor, surely that is a good place to begin a wood quality improvement programme.

What to look for: characteristics one might consider?

(1) Microfibril angle: some features and consequences

The microfibril angle (MFA) relates to the winding angle of the cellulose microfibrils in the S_2 layer of softwood tracheids (Figure 3). Near the pith the MFA is large, declining gradually from pith to cambium (Figure 4). The MFA has two major effects on wood properties. First, the stiffness of the cell wall increases enormously (five-fold) from pith to cambium as the microfibril angle decreases from c. 40° to 10° (Figure 5). Secondly, longitudinal shrinkage increases with microfibril angle but in a highly non-linear manner (Figure 6) and is responsible for some degrade

on drying, especially crook. There is an excellent theoretical understanding, and fundamental equations have been developed which describe both behaviours extremely well (Cave, 1968, 1969; Barber & Meylan, 1964).

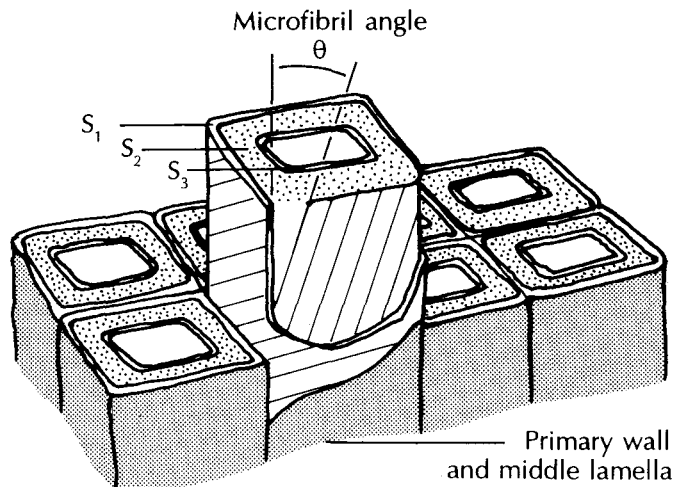


Figure 3. Orientation of the microfibrils in the S_2 layer.

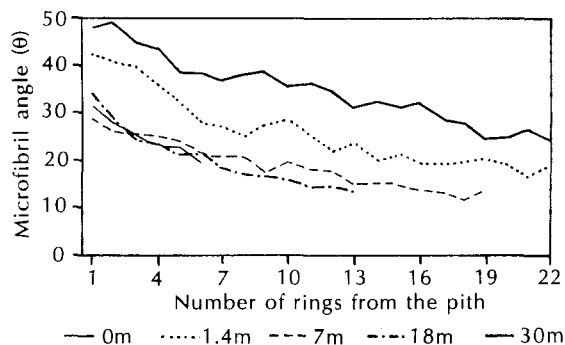


Figure 4. Variation in microfibril angle within a tree (after Donaldson, 1992).

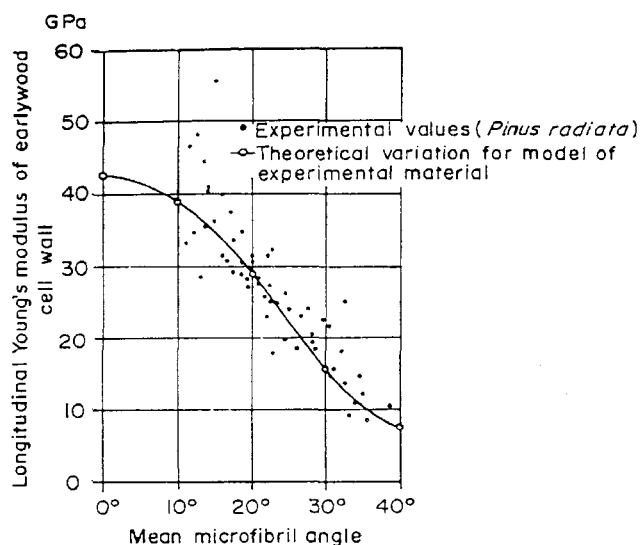


Figure 5. Axial stiffness of the cell wall itself as a function of microfibril angle (after Cave, 1968).

(2) Density or microfibril angle

There are numerous statements to the effect that density is the most important characteristic in determining the properties of wood. Zobel and van Buijtenen (1989, p 15) argue that ... Spe-

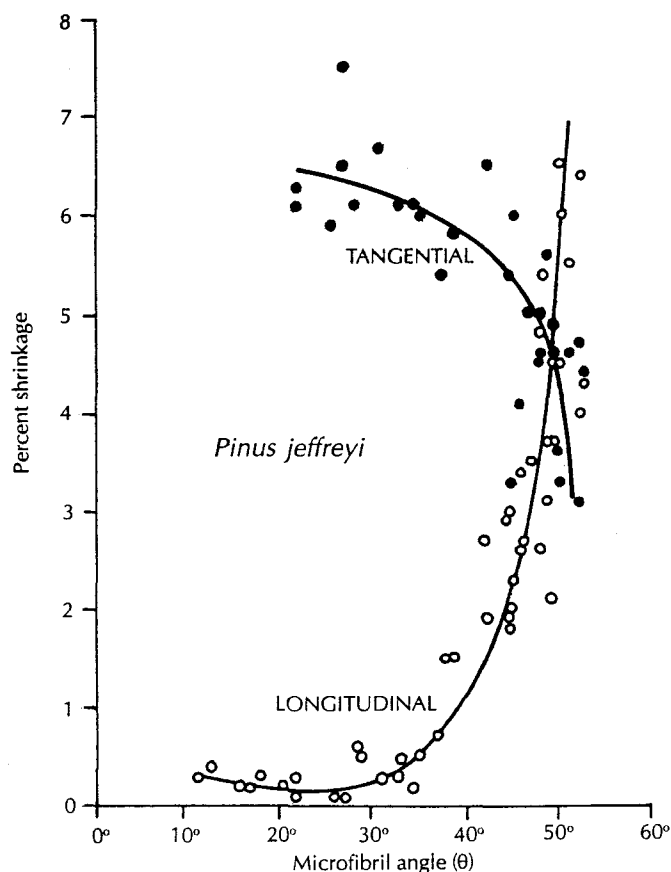


Figure 6. Shrinkage as a function of microfibril angle (after Meylan, 1968).

cific gravity is of key importance in forest products manufacture because it has a major effect on both yield and quality of fibrous and solid wood products and because it can be changed by silvicultural manipulation and genetic manipulation. Therefore, specific gravity largely determines the value and utility of wood and overshadows the importance of other wood properties.

With regard to radiata pine, Bunn (1981) states ... Basic density is probably the single most important intrinsic wood property for most wood products, particularly if we are contemplating adopting short rotations. While Bamber and Burley (1983) point out ... Of all the wood properties density is the most significant in determining end use. It has considerable influence on strength, machinability, conversion, acoustic properties, wearability, paper yield and properties and probably many others. Finally, to demonstrate that we keep good company, ... Without doubt density is the most useful indicator of wood properties (Walker, 1993 p 153).

Higher density would result in an increased kraft yield, superior furniture as hardness of radiata pine is perceived to be inadequate, and a higher grade out-turn of structural timber. With regard to kraft pulp, one could usefully ask the question: what wood characteristics can be manipulated to improve quality? Spruce and pine are genera of comparable density, yet the former trades at a premium, so price is not simply a matter of density; parameters such as coarseness are also relevant. Having said that, current opinion has identified density as being the characteristic whose manipulation would be most likely to benefit the kraft pulping industry: a 10% increase in pulp yield and digester throughput are appreciated readily. With regard to hardness, the quality end of the furniture market can be addressed now by the FRI's wood-hardening technology, so the poor intrinsic hardness and modest density of clearwood become less of an issue. The most compelling case for an increase in wood density is sum-

marised in the statement that ... A modest increase in density (say 10%) will improve the strength of framing timber to such an extent that even though knots are 50-70% larger the timber remains as strong (What's New in Forest Research No. 30, based on Harris *et al.*, 1976). This statement was made in the context of the effect that pruning and wide spacings would have on properties of the second log, and the difficulties of producing framing timber from such stands.

Comparative studies between radiata pine and favoured timbers of the Northern Hemisphere indicate that the mechanical properties of radiata pine fall short of those for commercially important species of the Northern Hemisphere (Walford, 1991): of the 11 species examined, radiata pine was ranked 7=11 in strength and only 11/11 in stiffness. Poor structural performance is a problem, as there are limited alternative markets for low-grade timber. It is important to note that it is **stiffness** which is the poorer property, not strength.

The phenomenon of poor grade out-turn from radiata pine is an issue nationwide (Figure 7). A SAWMOD simulation of the grade out-turn from a 30-year-old unpruned stand resulted in 36%, 38%, 40%, and 58% of the timber in the butt, 2nd, 3rd and 4th log failing to make the Australian F5 grade (Cown, 1992b p28). There is a far greater financial return from improving the lower grades (generally from the corewood zone) than in lifting grades in the outerwood: raising material to F5 grade (Framing) is worth \$100/m³. The same report noted repeatedly that the principal limitation to radiata pine in structural markets is its lack of stiffness, and that ... The stiffness of timber is closely related to density and, to a lesser extent, knot size [while] strength is more closely associated with knot size (p30).

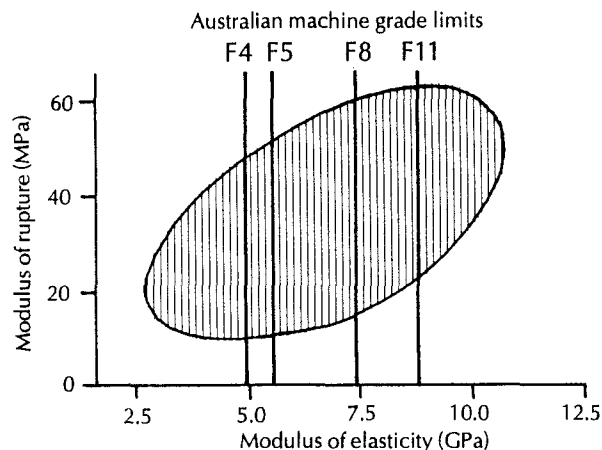


Figure 7. Grade out-turn from 28-year-old radiata pine (adapted from Cown, 1992b).

Recently, the butt logs of 48 trees from the Canterbury Plains were milled to produce 399 boards (Addis Tsehaye *et al.*, 1995a, b). After drying, dressing to 90 x 35 mm and machine stress grading the boards were tested destructively to obtain stiffness, strength and clearwood density values. Finally, the trees were ranked and grouped according to the mean density and stiffness of their boards as determined in the laboratory. The grade out-turn of the superior, average and inferior tree groups were recorded (Tables 1 and 2). Selection according to density does not appear to be a very effective method for identifying better structural timber. Instead the issues are how best to identify intrinsically stiff seedlings and to decide what wood characteristics are controlling.

If, for other reasons, one were to pursue an increase in wood density one might bear in mind that an outerwood density improvement programme would have limited benefits for the corewood zone, where the majority of low-grade timber is found. So, at the very least, one might wish to reverse an earlier argu-

Table 1. Machine stress grade distribution for all the boards from the butt log, from trees ranked according to density (Addis Tsehaye *et al.*, 1995a, b).

Group	# of trees	# of boards	Mean density kg/m ³	Mean MOE (GPa)	<i>Australian Machine Stress Grades</i>		
					F4 & below	F5	F8 & above
Five densest trees	5	42	542	6.8	52%	24%	24%
Mean	38	315	489	6.6	52%	30%	19%
Five least dense trees	5	42	450	5.9	64%	29%	7%

Table 2. Machine stress grade distribution for all the boards from the butt log, from trees ranked according to stiffness (Addis Tsehaye *et al.*, 1995a, b).

Group	# of trees	# of boards	Mean density kg/m ³	Mean MOE (GPa)	<i>Australian Machine Stress Grades</i>		
					F4 & below	F5	F8 & above
Five stiffest trees	5	41	527	8.4	29%	24%	46%
Mean	38	311	486	6.5	54%	30%	16%
Five least stiff trees	5	47	489	4.7	71%	23%	6%

ment: by concentrating on corewood density one has the potential to capture a modest (but very significant) increase in density while also cashing in on 50% of the greater increase in density (more variation) in the outerwood.

An heretical thought: industry has disentangled the confusion between wide rings (fast growth) and juvenile wood as to the cause of poor wood quality, but still retains the simplistic notion that density accounts for improved wood quality in outerwood. Density only increases by about 50% from pith to cambium in 30-year-old radiata pine and so should account for an equivalent increase in tensile strength and stiffness. Clearly, a modest increase in density, from pith to cambium, is not capable of providing the increased performance that is frequently attributed to it. One mistakes an accident of wood for the essence of its character who think that by merely adding to its substance one achieves the improved performance necessary for its acceptance as a quality product. The improved stiffness from pith to cambium is not due primarily to the increased mass of cell wall material (quantity) but to a profound change in its quality. Rather than focusing solely on the **quantity** of matter in a piece of wood (its density), one might consider also the **quality** of the material in the cell wall. What other industry would confuse increased production with improved quality?

Superior stiffness will result in an improved grade out-turn. Of all the intrinsic wood characteristics the microfibril angle (MFA) has the greatest influence on this property. Stiffness of wood increases **five-fold** as the microfibril angle decreases from c. 40° to 10° (Figure 5). An indication of the variation in microfibril angle within and between trees of radiata pine is shown in Figures 4 and 8, with MFA decreasing from pith to cambium and up the stem. Relating the MFAs in Figure 8 with the stiffness-MFA plot in Figure 5 gives an indication of the potential benefits arising from selection of trees having below average MFA. In this case selection would be for corewood MFA and not outerwood MFA. As with density, it should be possible to select on the basis of MFA at a very early age as the MFA always decreases with age. Having selected a clone with a low initial MFA there are only two trends, either the MFA declines noticeably with further growth rings or it declines only gradually (Figure 9).

Existing tree-breeding programmes have identified families

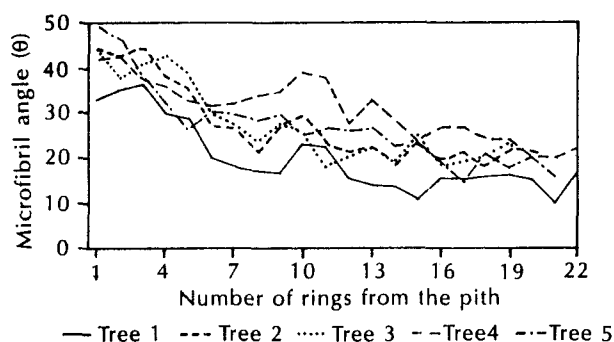


Figure 8. Variations in microfibril angle between trees (after Donaldson, 1992).

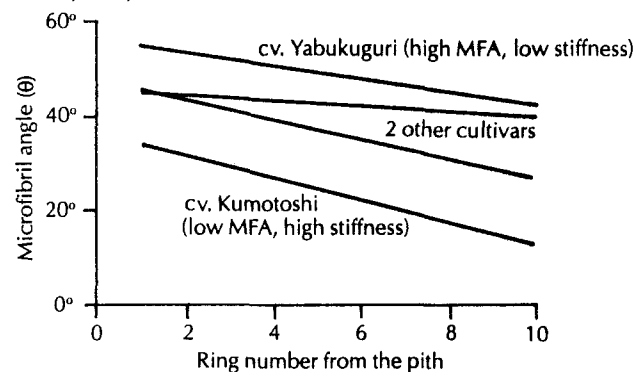


Figure 9. Variations in microfibril angle observed in cultivars of *Cryptomeria japonica* (after Fujisaki, 1985).

which collectively cover a wide range of density, from the low-density breeds of relevance to mechanical pulping as well as the high-density breeds of more general utility. There is no suggestion that these should be abandoned; rather one might consider selecting other desired properties such as stiffness from within these breeds, or at the very least screen to remove material that clearly has other less desirable heritable traits.

(3) Tracheid length or microfibril angle

Early optical measurements of MFA were extremely tedious.

This encouraged the alternative approach of obtaining control of MFA indirectly, which sought to use an empirical relation between MFA (θ) and length (L) of individual tracheids, and measure tracheid length rather than MFA. Two statistical equations have been advocated, $L = a + b \cot \theta$ and $L = a - b \theta$. To give one example of this approach, Echols (1955) found that tracheid length accounted for 91% ($r = -0.956$) of the variation in microfibril angle in *Pinus elliottii*. With fast, modern X-ray diffraction methods to measure MFA, this approach is no longer necessary unless selection for fibre length is, in itself, an attractive option. In any selection programme it is better to select directly for the characteristic that it is desired to improve, rather than to approach the desired characteristic indirectly. Although Echols' correlation coefficient is so large that it would not matter greatly if tracheid length were taken as a surrogate measure for microfibril angle, poorer correlation coefficients appear in the literature. Thus Hirakawa and Fujisawa (1995) obtained a modest correlation coefficient ($r = -0.69$) for latewood tracheids of *Cryptomeria japonica* (Figure 10).

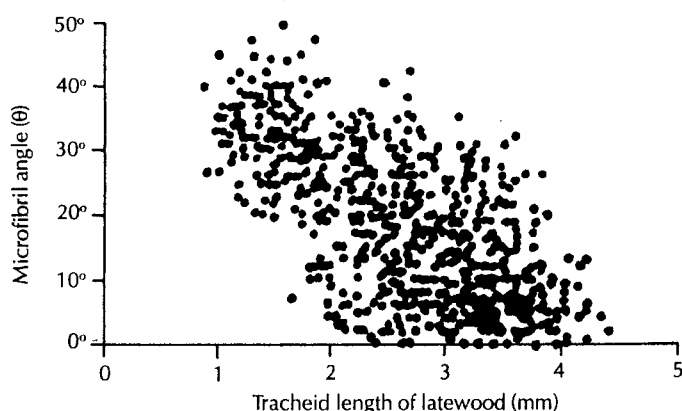


Figure 10. Tracheid lengths and microfibril angles for macerated latewood tracheids of six clones using tissue from the 2nd, 6th, 16th and 20th growth rings (after Hirakawa and Fujisawa, 1995).

The variation in tracheid length within a tree is shown in Figure 11. Both the spatial pattern and range of tracheid length (a four-fold change) mirror the behaviour of the MFA. Knowledge of the between-tree variations is limited. One study of nine 52-year-old trees (Kibblewhite, 1980) observed that the mean tree values varied by about 0.6 mm for both corewood (3.2-3.7 mm) and outerwood (4.1-4.8 mm), with corewood being defined as the first 15 growth rings. With ten 12-year-old thinnings the average tracheid length in corewood is reduced, ranging between 2.4 and 2.8 mm (Kibblewhite & Lloyd, 1983).

With kraft pulps tear strength is an intrinsic feature of the raw material, whereas burst and tensile strength can be developed by beating. Further, according to Zobel and van Buijtenen (1989) there is a minimum length, c. 2 mm, necessary to produce acceptable kraft pulp, and improved tear strength is most noticeable on increasing the tracheid length to about 3 mm. *It is when cells are near this "threshold length" that cell length variation can be of primary importance with regards to acceptable product quality (p19).* This implies that if one were to select for tracheid length one should focus on the corewood region, where tracheids are of this critical length. Even if corewood were to be processed predominantly as mechanical pulp there would be an advantage, as the somewhat longer fibres in the sheet would require less reinforcement from longer fibre stock. Selection of clones having longer tracheids in corewood would be justified only if measurement of MFA was too difficult or tedious (no longer true) and tracheid length was taken as an approximate surrogate: with the right facility measuring MFA becomes a routine.

Harris (1965) found that density and tracheid length varied

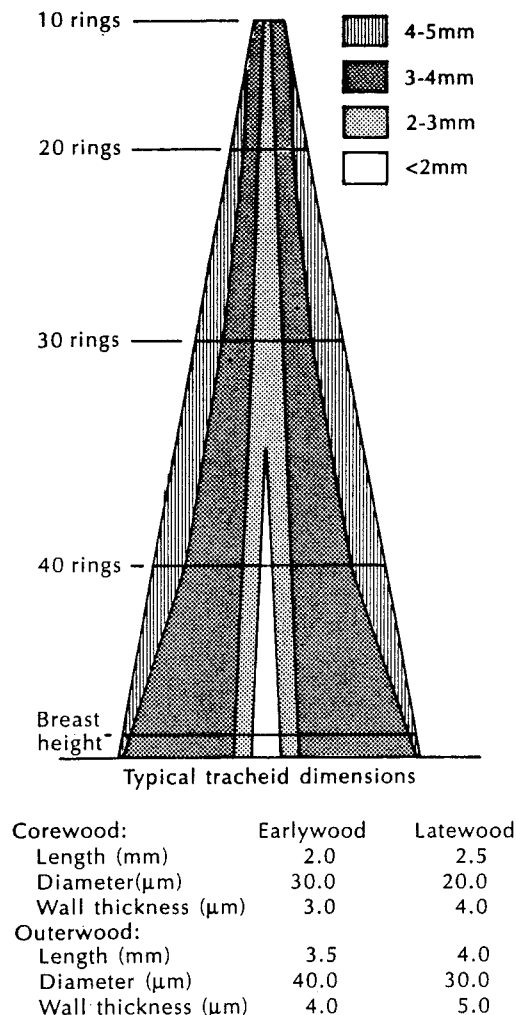


Figure 11. Variations in tracheid length within a tree (adapted from Cown 1992b).

independently between trees, so intuitively one should not expect a strong correlation between density and microfibril angle, or density and stiffness. So the trends in Tables 1 and 2 are explicable.

(4) Lignin content or microfibril angle

A reduction in lignin content would be of considerable benefit for the pulp and paper industry, especially in the manufacture of bleached kraft pulp where chemical would be saved in both cooking and bleaching.

Lignin content is higher in corewood than in outerwood (Uprichard, 1991). The high lignin content of corewood is expected as the S_2 layer is thin, and this is the layer which is low in lignin (and high in structurally-useful cellulose). Further, where the MFA is large the dispersion/distribution of microfibrils about their preferred orientation is large, $MFA \pm 1/3 MFA$ (Cave 1968). This imperfect alignment between contiguous microfibrillar lamellae suggests that they do not pack too tightly, leaving more space within the swollen cell wall for the deposition of lignin. Finally, there is a higher incidence of compression wood in corewood, and compression wood cells have thicker walls with a larger MFA and more lignin: an ancillary concern is the degree to which the presence of mild compression wood confounds our understanding of normal corewood (if such material exists).

A regression ($r = 0.73$) between lignin content and MFA by Saka (1984) relates to 20 softwoods: probably mostly from out-

erwood, but including five compression wood samples. Lignin content decreases with decreasing MFA (Figure 12). There is sufficient circumstantial data to suggest that an improvement in one characteristic will benefit the other, whether one selects for low lignin content or low MFA.

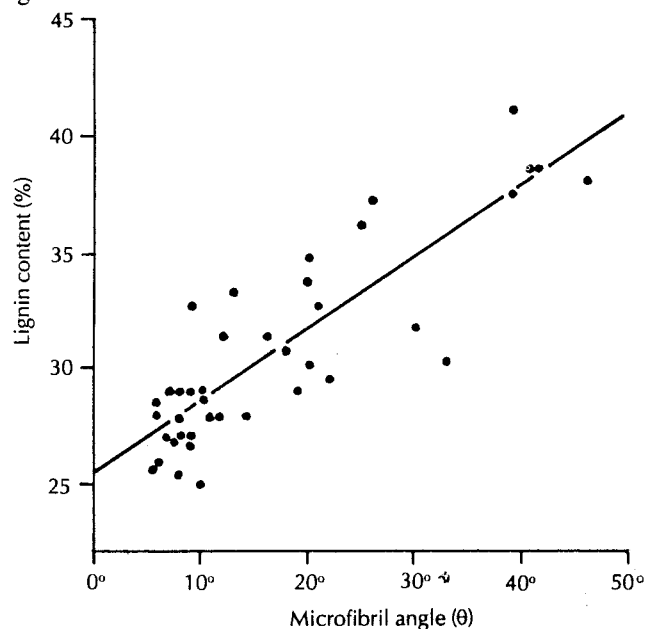


Figure 12. Variation in lignin content (LC) with microfibril angle (θ) for 20 softwoods together with the regression, $LC (\%) = 25.3 + 0.31\theta$ for which $r = 0.73$ (after Saka, 1984). The five points in the top right-hand corner are for compression wood samples.

(5) Spiral grain or microfibril angle

In radiata pine spiral grain is worse in the corewood zone and it increases in severity up the stem (Figure 13), unlike the MFA which is large at the base and decreases up the stem. Thus the worst effects of spiral grain are observed in the smaller top logs, whereas the worst effects of large MFA are found in the corewood of the butt log.

Although moderate spiral grain may have little direct effect on structural properties, warping of boards does affect the utility of timber. Cown (1992a) notes ... *There is strong evidence that spiral grain can contribute very significantly to the economics of processing*, i.e. its presence lowers the value of timber, by an estimated \$40/m³. Analysis after drying has indicated that 5° would be the critical point at which twist, arising from spiral grain, is sufficient to downgrade timber – and a mean grain angle of $5^\circ \pm 2^\circ$ is considered typical of the first 10 growth rings. There is a strong tendency for some trees to have high values with angles between 5° and 15°, while others have low values – $5^\circ \pm 5^\circ$, which suggests a strong genetic component (Cown *et al.*, 1991). However, focussing on a single characteristic can lead to inappropriate conclusions as other factors also accentuate twist. In New Zealand radiata pine, for example, the first 10 years of growth from the pith presents a special warping problem, as lumber tends to twist because of excessive spiral grain in combination with large (micro)fibril angles (Jozsa & Middleton, 1994). Spiral grain affects wood properties only because wood is anisotropic. Any characteristic that affects anisotropy in shrinkage and increases radial shrinkage gradients will exaggerate any twist arising from spiral grain. The large longitudinal shrinkage of wood with a high MFA (Figure 6) is capable of accentuating the effects of spiral grain, as well as inducing other distortion such as crook. Thus, structural performance can be improved by modifying the cellulose microfibril angle while coincidentally also reducing the propensity of timber to twist – without the need to manipulate spiral grain. Furthermore, some of the worst effects

of twist can be mitigated during processing: by segregation of wood types, by high temperature drying using heavy stack weights, with more uniform air-flow, by more accurately determining the end-point to avoid over-drying and by dressing or fingerjointing subsequently.

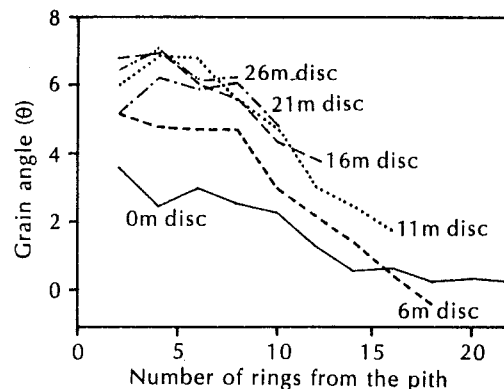


Figure 13. Pattern of spiral grain in radiata pine, averaged from 50 trees (after Cown *et al.*, 1991).

When to look: sampling young stems?

It would clearly be advantageous if one could use the quality of seedling wood as an indicator of the characteristics likely to be found in outerwood. Current research is proceeding to ascertain whether a high or low microfibril angle in a seedling from a particular clone is likely to reflect the microfibril angles to be found in the mature tree.

Traditionally, seedling wood has been an unreliable indicator. There are many reasons for this, most of them associated with the sort of treatment that the seedlings are subjected to as part of the afforestation process. In the nursery seedlings are root pruned, which would disrupt normal cambial activity and generate growth stresses. At establishment the seedlings are planted quickly so that many end up at an angle to the vertical. This would induce an instant response in the plant which sets up mechanisms to correct any lean. Cambial divisions become more frequent on the lower side of the inclined stem, resulting in an eccentric growth of the stem, and where the tracheids produced by the cambium display typical compression wood characteristics which include higher than normal microfibril angle. This is perfectly normal. It can never be "bred out" of the system, as it is the seedling's way of counteracting the uneven forces of gravity acting on the leaning stem.

A further difficulty in using seedling wood as an indicator of clonal quality results from the many fine needle traces passing through the wood. These are vascular connections to the epicormic needles on the stem.

Notwithstanding these obvious difficulties, there is a good likelihood that we can establish reliable techniques for micro-testing small samples of clearwood from the first growth ring. Because the vascular cambium reacts very quickly to external stresses and changes in environment any reduction in seedling disturbance is likely to have beneficial results in seedling quality, and as a consequence to the quality of the wood that is laid down over the first few growth rings.

Conclusions: benefits to be expected from selecting seedlings with a lower microfibril angle

Nietzsche's works are rich in aphorisms. The notion that "*in matters of fact we believe what we want*" suited that philosophic relativist, but a single-minded pursuit of density as the exclusive wood quality trait displays the same characteristic. To search more widely does not mean that the benefits of previous identification/selection for density should be abandoned; rather that selection of clones with small microfibril angles should come

from that population. Such selection need not be exclusive and should include the screening to remove clones having undesirable traits, especially large spiral grain.

A decrease in the microfibril angle of 5° would be a realistic target, bearing in mind the natural variation that one might reasonably expect (Figure 14) and applying a modest selection intensity of, say, 1 in 10. The benefits will accrue largely in corewood which is where one should begin such a wood-quality-improvement programme.

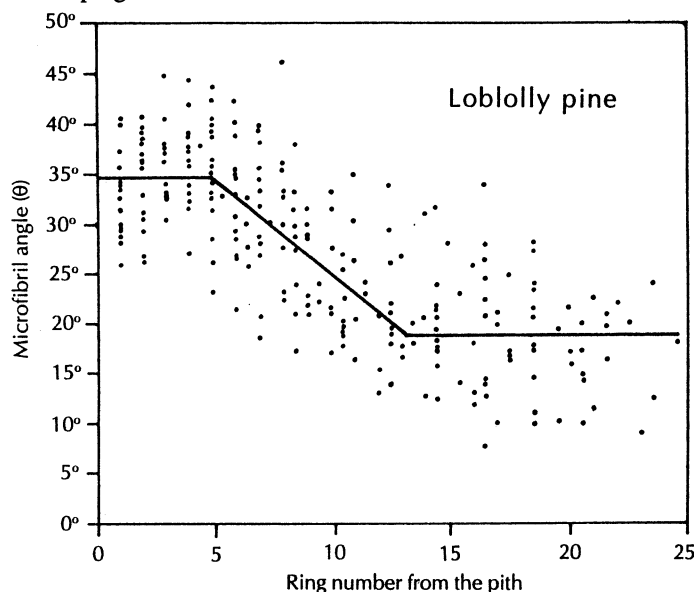


Figure 14. Variation in microfibril angle with age for 21 *Pinus taeda* trees (after Ying *et al.*, 1994).

One might reasonably expect:

- an increase in corewood stiffness of the order 25-50%, equivalent to raising the machine stress grades of structural timber by at least one grade, e.g. F4 to F5;
- an increase in corewood tracheid length of about 0.5 mm, so improving tear strength;
- a reduction in timber warp (but we need to develop a model to explore the interactions between spiral grain, compression wood and microfibril angle to understand the problem better).

Acknowledgements

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