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Cell wall structure and wood properties determined by acoustics – a selective review

C.-L. Huang, H. Lindström, R. Nakada, J. Ralston

Abstract The cell wall of wood tracheids is made up of various layers, distinguished from one other by the alignment of the innumerable, fine crystalline cellulose microfibrils within each layer that helically wind about the cell lumen. Microfibrils themselves are embedded in a more compliant, water-reactive matrix of amorphous lignin and hemicelluloses. The average inclination of microfibrils relative to the axis of the cell affects axial rigidity and dimensional stability of wood which are the two most important properties of wood. High and variable microfibril angles can be found in juvenile and compression wood, thus resulting in variations in product performance of forest products. For instance, seemingly identical trees in a plantation can have moduli of elasticity that differ by a factor of two or more. This is why the future is often seen in engineered wood products, where wood may be chipped, fiberised and blended before being glued together again: the average property values are little changed, but the range—the variability—is greatly reduced. There is the opportunity for better wood allocation and processing of timber, if averaged values for individual log characteristics, such as average microfibril angle, can be identified before the processing. In parallel there is genetic potential to select trees with low average microfibril angles. Unfortunately, determination of the average microfibril angle is a time-consuming, laboratory-based task. Preferably, a non-destructive, simple, field-hardened method should be employed that reflects the average microfibril angle in a given piece of wood. For this reason, acoustic methods have been developed to measure the velocity of sound propagation directly related to the stiffness of wood and in turn is dependent on the ultrastructure of the tracheid cell wall. In the fundamental equation, $E_{dynamic}=\rho V^2$, the acoustic modulus is derived from two components, density, ρ, and velocity of sound, V. The latter relates to the intrinsic wood quality and ultrastructure of the tracheid wall. It is shown that acoustic methods can sort and grade trees and logs according to their suitability for structural lumber and for a range of fiber properties of interest to papermakers. Thus, acoustic methods have applications in tree breeding, harvesting, and wood processing.

Bestimmung der Zellwandstruktur und der Holzeigenschaften durch akustische Methoden – eine übersicht

Zusammenfassung Die Zellwand von Holztracheiden besteht aus verschiedenen Schichten, die sich von einander durch eine Aneinanderreihung von unzähligen feinen kristallinen Zellulose-Mikrofibrillen in jeder der Schichten unterscheiden, die sich helikal um das Zelllumen winden. Die Mikrofibrillen selbst sind in eine wasser-reaktive Matrix aus amorphem Lignin und Hemizellulosen eingebettet. Der durchschnittliche Neigungswinkel der Mikrofibrillen relativ zur Achse der Zellen beeinflusst die axiale Steifigkeit und die Dimensionsstabilität des Holzes, die beiden wichtigsten technischen Eigenschaften von Holz. Steile und variable Mikrofibrillenwinkel können in juvenilem und Druckholz gefunden werden, wodurch sich Unterschiede in der Verarbeitung von Holzwerkstoffen ergeben. Beispielsweise können scheinbar identische Bäume in einer Plantage Elastizitätsmoduli aufweisen, die sich durch einen Faktor von zwei und mehr unterscheiden. Aus diesem Grund wird die Zukunft oft in technischen Holzprodukten gesehen, wo Holz zerspant, zerfasert und gemischt wird, bevor man es wieder zusammenleimt: die durchschnittlichen Eigenschaften werden wenig verändert, aber die Bandbreite—die Variabilität—wird stark reduziert. Können durchschnittliche Werte für individuelle Holzbalkencharakteristika, wie der Durchschnitts-Mikrofibrillenwinkel vorher bestimmt werden, besteht die Gelegenheit für eine bessere Holzauswahl und -verarbeitung. Parallel dazu gibt es ein genetisches Potential, um Bäume mit niedrigen Durchschnitts-Mikrofibrillenwinkeln zu selektieren. Leider ist die Bestimmung der Durchschnitts-Mikrofibrillenwinkel eine zeitaufwendige, auf das Labor bezogene Aufgabe. Vorzugsweise sollte eine zerstörungsfreie, einfache außen erprobte Methode eingesetzt werden,

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die den Durchschnitts-Mikrovibrillenwinkel in einem gegebenen Holzstück reflektiert. Aufgrund dessen wurden akustische Methoden entwickelt, um die Geschwindigkeit der Schallausbreitung zu messen, die direkt mit der Festigkeit des Holzes korreliert und damit auch abhängig ist von der Ultrastruktur der Zellwand. In der Grundgleichung, $E_{dynamic}=\rho V^2$, wird der akustische Modulus von zwei Komponenten abgeleitet, der Dichte, ρ, und der Schallgeschwindigkeit, V. Letztere bezieht sich auf die intrinsische Holzqualität und die Ultrastruktur der Tracheiden-Wand. Es wird gezeigt, dass die akustische Methode in der Lage ist, Bäume und Rundholz gemäß ihrer Eignung für Bauholz und für eine Bandbreite von Fasereigenschaften, im Interesse der Papierhersteller, zu sortieren und einzuteilen. Auf diese Weise finden akustische Methoden Anwendung bei der Aufzucht von Bäumen, ihrer Abholzung und Verarbeitung.

1
Introduction

Performance and the potential value of products depend on a wide range of interlinked fundamental wood characteristics. These are influenced by the genetics, growth conditions and silviculture, and by the age at which the trees are harvested. Subsequently, the wood characteristics are modified during processing to form the end product. Across this value chain certain underlying characteristics and properties have been identified as being influential in the conversion and use of timber. The minimum technical considerations, both for the sawmiller and the consumer, are that the lumber is stiff, and that it remains straight and stable. Stiffness, straightness and stability are all more problematic in juvenile wood (the first-formed growth rings nearest the pith) compared with those in outerwood. The reasons why these properties are so variable requires an understanding of the wood ultrastructure; that in turn suggests ways in which logs and lumber might be sorted in the future.

Where biological and synthetic materials are considered as structures, it is axiomatic that "form follows function". Gordon (1978), Gordon and Jeronimidis (1974), and more recently Mosbrugger (1990), Mattheck and Kubler (1995) and Lichtenegger et al. (1999) interpret mechanical performance of trees in terms of the tapered cantilevered stem, comprised of relatively thin-walled hollow cells, and the helical winding of the cellulose microfibrils within the cell wall layers. In short-rotation plantation softwoods, the main concern is on the physical and mechanical properties of wood from rings nearest the pith (juvenile or corewood), laid down at a time when flexibility of the young stem or stem leader was an important feature. In this context, the most critical characteristics are the microfibril angle (Preston 1934, 1974; Cave 1968, 1969; Cave, Walker 1994; Walker, Butterfield 1996; Butterfield 1998; Lindström et al. 1998), density (Bamber, Burley 1983; Zobel, van Buijtenen 1989; Cown et al. 1999; USDA 1999) and occasionally the spiral grain (Cown et al. 1991, Haslett et al. 1991). The key properties in which these characteristics are expressed are toughness (Jeronimidis 1980; Ashby et al. 1985), stiffness (Cave 1968, 1969) and stability, i.e. the tendency of wood to warp during or after drying (Harris, Meylan 1965; Megraw et al. 1998; Ormarsson 1999).

2
Wood as a porous fibrous composite

2.1
Influence of density

The density of oven-dry cell wall material, ρ_{wall}, is about 1500 kg/m^3. This value is true for all woods, whether balsa or teak (Weatherwax, Tarkow, 1968). Most commercial softwoods have oven-dry densities that lie between 400 and 600 kg/m^3 implying that the cell wall occupies on average about one-third of the volume and that the other two-thirds are available for sap in the living tree or is occupied by air when cut and dried as lumber.

Easterling et al. (1982) observed that the anisotropic behaviour of balsa and other woods is determined, in part, by the properties of the cell wall material, and, in part, by the dimensions and shape of the cells themselves. They distinguished between the properties of the cell wall material (the quality of the cell wall including ultrastuctural features such as the microfibril angle) and mere mass (the quantity of matter).

They noted that the stiffness modulus of a wood parallel to the grain, E_{axial}, is that of the cell wall itself, E_{wall}, scaled down by the fraction of the section occupied by the cell wall. Doubling the density, ρ, obviously doubles the fraction of the section occupied by the wall, and therefore doubles the modulus:

$$E_{axial} = E_{wall}(\rho/\rho_{wall}) \quad (1)$$

However, when wood is loaded across the grain all the individual walls of the hollow cells deflect like beams and wood behaves like any porous body:

$$E_{tangential} = E_{wall}(\rho/\rho_{wall})^3 \quad (2)$$

Gibson and Ashby (1997) present the experimental data of Easterling et al. (1982) for balsa together with Young's modulus for various other woods (Fig. 1), normalised for the density of cell wall tissue (1500 kg/m^3) and its axial modulus, $E_{cell\ wall}$ (35 GPa). The ratio for the moduli $E_{axial}/E_{tangential}$ in Fig. 1 increases to almost 100 for low-density balsa.

In Easterling et al. (1982) the density of the balsa samples ranged from 78 kg/m^3 to 218 kg/m^3. On the basis of density alone the axial stiffness would be expected to increase by a factor of 2.8 (218/78). However, the modulus increased by a factor of 6.5, from 0.9 to 5.9 GPa. The ratio between the two (stiffness change: density change), a factor of 2.3 (6.5/2.8), was attributed to changes in the mechanical properties of the cell-wall material.

2.2
Influence of the cell wall ultrastructure

Our review considers the behaviour of softwoods, which have simple cellular structures (Fig. 2) compared to hardwoods. Some 95% of the cells of softwoods are tracheids. These are long (1–4 mm), thin-walled (2–5 μm), and narrow (20–50 μm). The long hollow cells are aligned

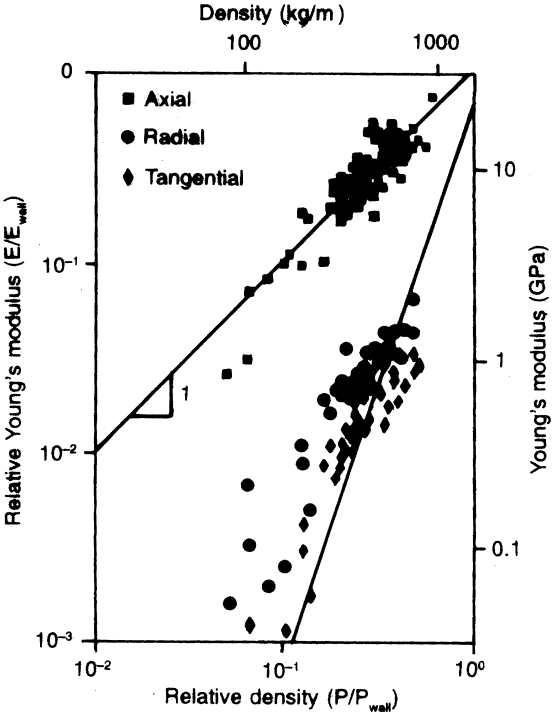

Fig. 1. Young's modulus for various woods plotted against density (after Gibson and Ashby 1997)
Abb. 1. Youngs Modulus für verschiedene Holzarten gegen Dichte aufgetragen (nach Gibson und Ashby 1997)

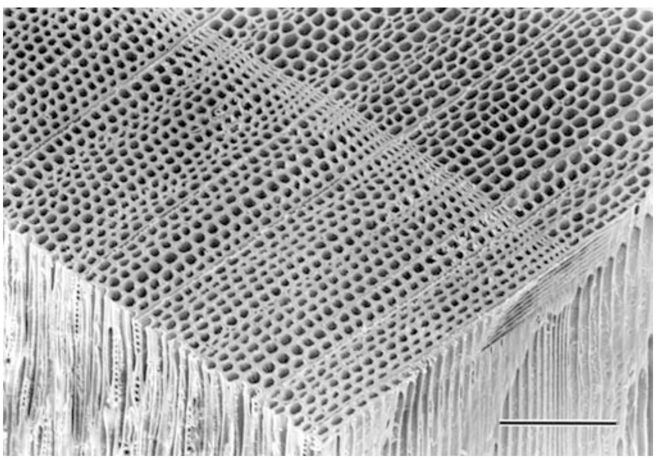

Fig. 2. Three-dimensional view of a wood block of *Chamaecyparis obtusa* showing the simple structure of coniferous wood on transverse (top), tangential longitudinal (left) and radial longitudinal (right) face. Note the thick-walled, small lumened tracheids in the latewood and the thin walled large lumened tracheids in the earlywood. Scale bar = 200 micrometer
Abb. 2. Dreidimensionaler Blick auf einen Holzblock der *Chamaecyparis obtusa,* der die einfache Struktur von Nadelholz transversal (oben), tangential längs (links) und radial längs (rechts) zeigt. Dick-wandige, englumige Tracheiden in Spätholz und die dünn-wandigen, weitlumigen Tracheiden in Frühholz. Maßstab = 200 Mikrometer

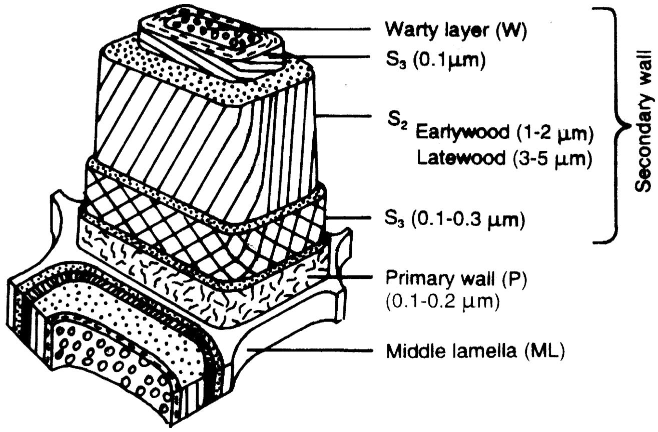

Fig. 3. A schematic diagram to illustrate the general structure of the tracheid cell wall and the dominant helical orientation of the cellulose microfibrils within each wall lay
Abb. 3. Ein schematisches Diagramm, um die allgemeine Struktur von Tracheiden-Zellwänden und die dominante helikale Orientierung der Cellulose-Mikrofibrillen in jeder Zellwandschicht darzustellen

approximately parallel to the axis of the stem. The cell wall itself is a multilaminate composite (Fig. 3). The individual cell wall layers are distinguished from one another by the orientation of the crystalline cellulose microfibrils within each layer. The microfibrils are very long (many microns) and thin (2.5–3.5 nm) and contribute largely to the stiffness and strength of the wood. Model structures, made by helically winding glass fibers are coated with resin into hollow tubes, mimic wood, but cannot replicate the fact that an individual tracheid will have over a million densely-packed microfibrils embedded in the non-crystalline matrix of hemicelluloses and lignin. Cellulose accounts for about 42% of the dry matter in softwoods, with the non-crystalline hemicelluloses, lignin and extractives (resins and gums) accounting for the balance. The general inclination of the microfibrils to the tracheid axis defines the microfibril angle that varies between cell wall layers. The thickest layer, the S_2 layer, accounts for 60–90% of the volume of the whole cell wall. When the microfibril angle in the S_2 layer is small, it is legitimate to ignore the contribution of the other layers to axial stiffness as the microfibril angle in these other layers is invariably large, >60°. The crucial feature in conifers is that the microfibril angle in the S_2 layer falls from 40–60° in the wood near the pith to 5–15° in outer growth rings. This gradual change in the microfibril angle results in a three to five-fold increase in the stiffness of the cell wall in the axial direction (along the grain).

The importance of the helical winding of cellulose in natural fibers for mechanical properties has long been recognised. At its simplest the cellulose microfibrils can be considered to act as stiff springs embedded in a weak matrix with the stiffness of wood increasing five-fold as the microfibril angle decreases from 40° to 10° (Walker, Nakada 1999). For small microfibril angles, the tensile or compressive modulus along the grain is high and is determined largely by the stiffness of microfibrils. At large angles (>40°), the axial stiffness is low and controlled by the shear properties of the weak matrix of hemicelluloses and lignin. Theoretical modelling (Cowdrey, Preston 1966; Cave 1968, 1969) which acknowledges the complexity of the tracheid wall structure describes the observed axial stiffness reasonably well (Fig. 4). Astley et al. (1998) using finite element analysis have incorporated the complex, irregular geometric arrangement of cells derived from

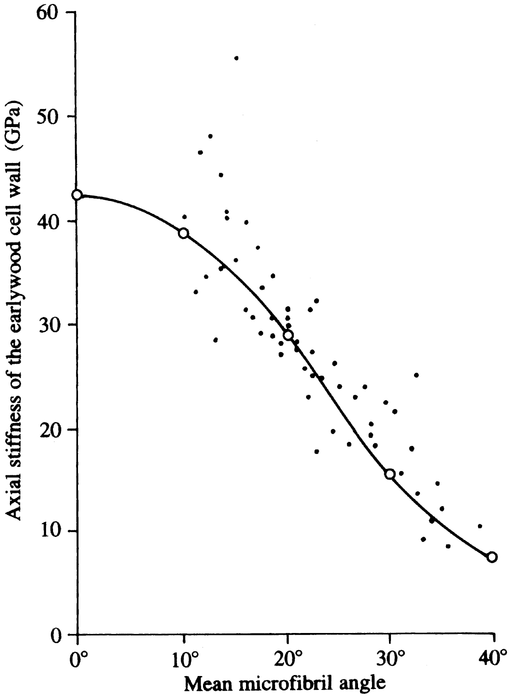

Fig. 4. The relationship between longitudinal Young's modulus and microfibril angle (experimental data) for *Pinus radiata* (according to Cave 1968)
Abb. 4. Die Beziehung zwischen dem longitudinalen Youngs Modulus und dem Mikrofibrillenwinkel (experimentelle Daten) für *Pinus radiata* (nach Cave 1968)

actual wood samples together with a realistic representation of the cell wall as a multilayer laminate. They obtain good agreement between derived and observed mechanical properties for diverse cell geometries. While the earlier cell wall models indicated a 5-fold increase in the axial modulus as the microfibril angle declines from 40° to 10°, Astley et al. (1998) suggest a figure of 2.5 for wood having a density of 400 kg/m^3.

2.3 Form and function

In a living tree, stiffness, strength and toughness are crucial properties—as is sap-flow—although their importance changes with the tree age. When young, the tree needs to be flexible in order to bend toward the light and sway in the wind; therefore it produces corewood with much larger microfibril angles than are found in the outerwood. At the same time the multi-laminate cell wall provides a very high fracture toughness at the expense of some loss of ist potential stiffness. Toughness is so important that even the stiffest timbers rarely have a microfibril angle less than about 10° in their outerwood, with the optimal trade-off between stiffness and toughness occurring at a microfibril angle of about 15° (Gordon, Jeronimidis 1980). High fracture toughness under axial load is achieved by energy absorption through shear failures at weak interfaces between microfibrils and the more compliant matrix as the microfibrils seek to align themselves with the applied load, leading eventually to buckling, i.e. there is failure between the microfibrils before the pull-out and the ultimate failure of the microfibrils (Jeronimidis 1976).

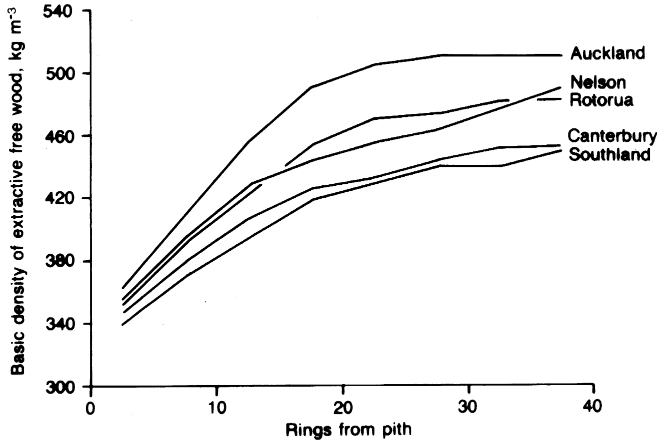

Fig. 5. Age-related density profiles for radiata pine growing in various regions of New Zealand (according to Bunn 1981)
Abb. 5. Altersbezogene Dichteprofile für *Pinus radiata*, die in unterschiedlichen Gegenden Neuseelands wächst (nach Bunn 1981)

However, in wooden structures stiffness and stability are the key properties, while fracture toughness is generally less critical as metal connectors between wooden members are designed to absorb energy—for instance in an earthquake. Both trees and wooden structures require strength, but in practice, sawmills measure stiffness and only predict or estimate the minimum strength of each piece of wood. Hence the emphasis on stiffness measurement. On the other hand, warp and instability of wood, as a result of anisotropic shrinkage, are of no relevance in trees, and only become major considerations in wood structures, because the timber is dried—a condition never experienced in the living tree and so not an evolutionary consideration.

3 Within-tree wood quality profiles

3.1 Characteristics of corewood in conifers

In practical terms, the defining feature of corewood or juvenile wood is the *steep* initial wood quality gradient: the magnitude of the density gradient (Fig. 5) is commented most frequently. In conifers, it is well known that the first 10 or so growth rings surrounding the pith, a "corewood" cylinder, is of inferior quality compared to wood further out. Less desirable characteristics of this corewood cylinder in conifers include the following (Zobel 1975):

- Low basic density (oven-dry matter) in some key commercial species.
- High moisture content before heartwood formation.
- A large cellulose microfibril angle in the S_2 layer.
- Spiral grain.
- Moderate to high longitudinal shrinkage.
- A lower percentage of cellulose.
- Short tracheids ("fibers").

These characteristics make lumber of low stiffness and strength prone to warp: and in chemical pulp the yields are slightly lower and the paper has low tear strength due to the short fibers.

These generalisations are of major relevance for fast-grown, short-rotation plantations, where the trees are harvested after only 15–30 years. In such situations at least half the merchantable wood is this poor-quality corewood. In consequence, as stands are harvested earlier, industry has had to face a steady deterioration in wood quality. This arises from the increased proportion of corewood, further aggravated by a much greater variability that arises from the rapidly changing properties within corewood itself. Fast growth is not the problem, it is rather the abundance of corewood arising from the shorter harvesting cycle (Kennedy 1995).

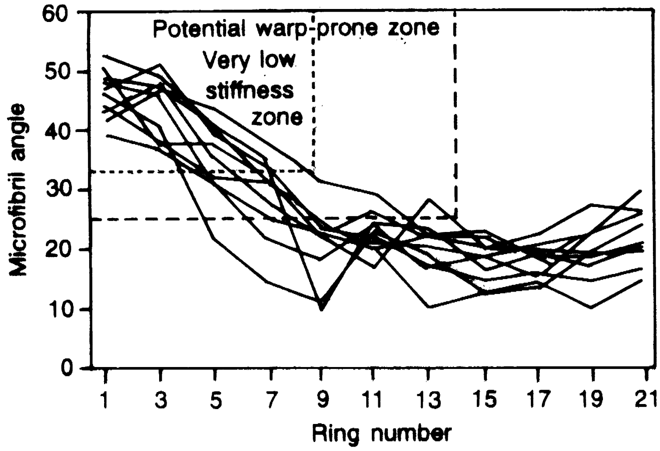

Fig. 6. Microfibril angle trends at breast height for ten trees produced from seedlings of *Pinus radiata* (adapted from Donaldson 1996)
Abb. 6. Trends der Mikrofibrillenwinkel in Brusthöhe für 10 Bäume aus Samen von *Pinus Radiata* gezogen

3.2
Within tree stiffness variation: influence of density and microfibril angle

For *Pinus radiata* the average increase in density over the first 30 years is between 30% and 50%, depending on the geographic region; so on the basis of density alone one would predict a 30–50% increase in longitudinal stiffness (see Eqs. 1 and 3). However, concurrent with the increase in density, there is a decrease in S_2 microfibril angle from around 40° to below 20° (Fig. 6) which results in a 2.5-fold increase in stiffness if the model of Astley et al. (1998) is accepted. Clearly in this species these two characteristics of corewood, low density and large microfibril angle, conspire together to reduce strongly the axial stiffness relative to that of outerwood. However, with certain other softwoods including *Cryptomeria japonica* density decreases for about the first 5 growth rings (Fujisawa et al. 1993); in such cases, the increasing stiffness due to smaller microfibril angle compensates for the falling density.

One can construct a wood-quality map delineating the range in axial stiffnesses of trees (Fig. 7) by plotting the mean stiffness value (MOE) against the mean density (ρ), species by species. The whole-tree stiffness-density data are biased in favour of the outerwood (>ring 10) as most of the data were gathered in the first half on the twentieth century when huge, mature trees were being taken from virgin forests. The relationship can be expressed in the general form:

$$\mathrm{MOE} = k\rho^{n}, \qquad (3)$$

where n is either 0.7 or 1.01 for hardwoods, and either 0.85 or 0.82 for softwoods, according to US and European data sets, respectively (Table 4–11a in USDA 1999; Table 2 in Lavers 1974), with a value of 0.78 for all the data combined. Statistically there is little to choose between a power series and a linear regression. Superimposed in Fig. 7 are lines for the calculated stiffness of wood with different microfibril angles. The experimental data lie within a wedge: the upper boundary of which corresponds to outerwood with a S_2 microfibril angle of 0° ± 7° (Pers. comm. Ian Cave); the lower boundary to wood having a microfibril angle of 45 ± 20°. These whole-tree values indicate that the less dense timbers, which are largely softwoods, have small microfibril angles, ca 10°, whereas the densest hardwoods achieve adequate stiffness despite modest microfibril angles, about 25°. The low-density softwoods are more efficient mechanically.

Whole-tree data disguise the enormous range in stiffness values observed in various parts of the tree, from pith to bark and from ground level to the uppermost merchantable part of the stem. Further, by presenting values for entire species the genetic differences between individual trees are averaged out as well. Within-tree variations in stiffness reflect changes in functional requirements. These differences in stiffness seem particular to different species and are caused by microfibril and density differences. As a visual representation, the entire range in stiffness variability found for a species can be encompassed in a “stiffness envelope” where the borders of the envelope are determined by variations in microfibril angle and density found for that species. Thus values obtained from young *Pinus radiata* (first 5 growth rings) and values obtained from outerwood of *Eucalyptus nitens* are found at or toward the extremes of two species-unique “stiffness envelopes” (wedges) in Fig. 8. (Evans et al. 2001, Lindström et al. in press). In the worst case, with radiata pine one might expect material from the first growth ring to have a microfibril angle of 45° ± 20° and a density of 350 $\mathrm{kgm^{-3}}$. In contrast, the best wood in ring 10 could have a microfibril angle of 10° ± 7° and a density of 500 $\mathrm{kgm^{-3}}$. This would give contrasting stiffnesses of 2.25 and 12.5 GPa respectively. An achievable goal for tree breeders of radiata pine is to locate and grow material having a microfibril angle of 30° ± 10° and a density of 400 $\mathrm{kgm^{-3}}$ at age 1, with an initial stiffness of 4.2 GPa. This would deliver such improved wood characteristics and properties as to blur the distinction between this new corewood and traditional outerwood values for fast-grown radiata pine.

3.3
Warp of lumber: the influence of the density and microfibril angle gradient

Distortion during drying and movement in service due to humidity changes are the greatest disincentives to the use of lumber. It generates *angst* among architects and much

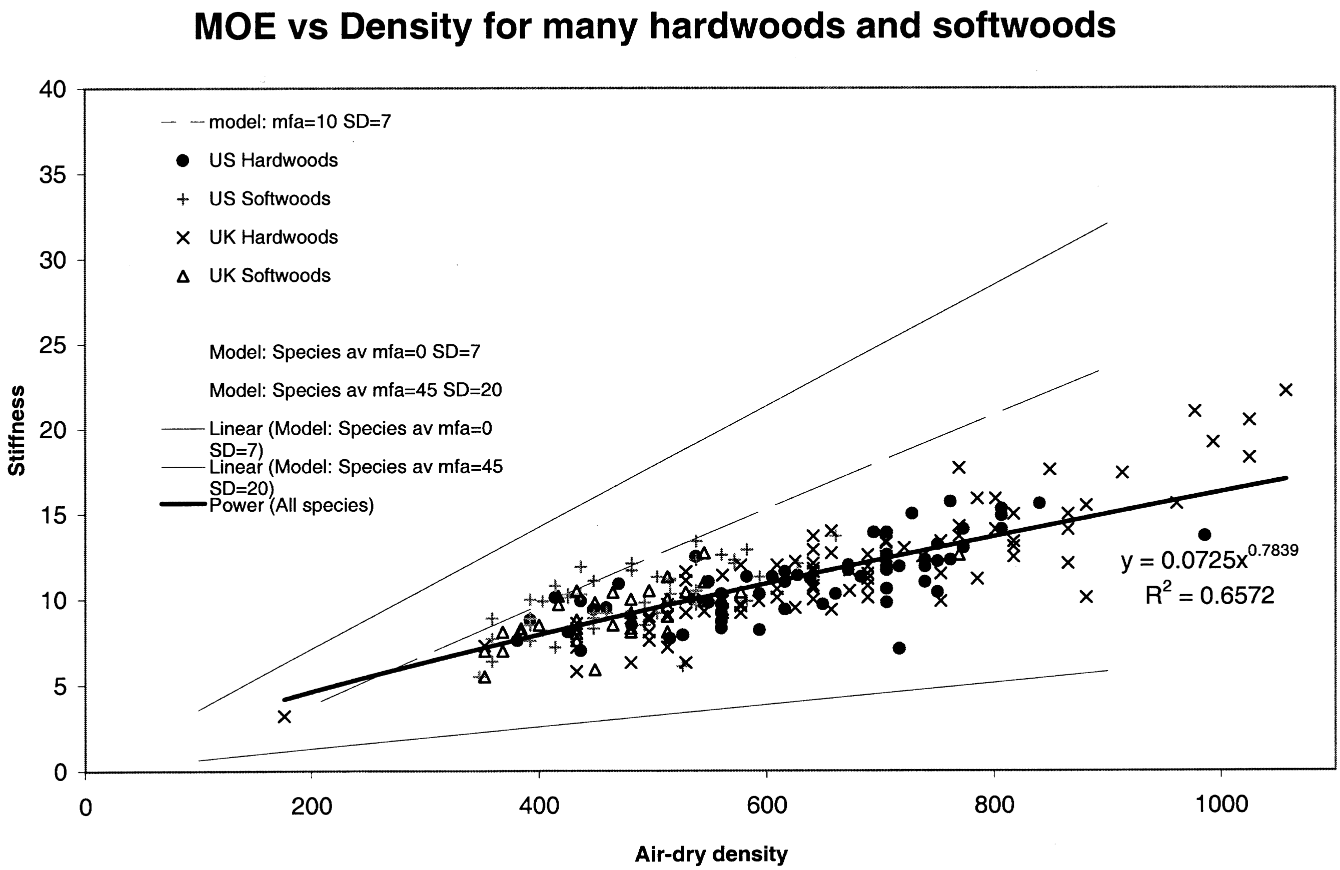

Fig. 7. Wood quality map incorporating the effects of density and cell wall ultrastructure for all species—averaged whole tree data. The dotted lines indicate theoretical stiffness values based on three levels of microfibril angle

Abb. 7. Karte der Holzqualität, die den Dichteeinfluss und die Ultrastruktur der Zellwand für alle Spezies enthält. Durchschnitt der gesamten Baumdaten. Die gepunkteten Linien zeigen theoretische Steifigkeitswerte an, die auf drei Größenbereichen der Mikrofibrillenwinkel basieren

litigation. Gaby (1972) observed that boards containing pith and boards containing both pith and compression wood are far more prone to distort due to the high microfibril angle and longitudinal shrinkage in both the very youngest wood and in compression wood (Fig. 11). The final moisture content influences the severity of the distortion, with more longitudinal shrinkage occurring at low moisture contents (Fig. 11). Exact Standards highlight the presence and problem of warp. In Japan, for example, only 6 mm of crook or bow is allowed over a three meter length of first grade dimension lumber (MAFF 1991), whereas traditional construction in New Zealand has been over-tolerant, permitting 25 mm bow and 10 mm crook in a 3 m length of 100 × 50 mm framing lumber (SANZ 1988). Understanding the principles of underlying bow and crook have resulted in generalized models of warp and thus the ways of minimizing warp (Ormarsson 1999), but industry still does not have predictive tools to identify and segregate warp until after the wood has undergone expensive processing.

No shrinkage occurs when absorbed sap is removed from the hollow centre, "the lumen", of the cells. Wood shrinks only when adsorbed water is removed from within the cell wall itself. The cellulose microfibrils restrain the cell wall from shrinking in the direction parallel to their axis and force the swollen, non-crystalline matrix of hemicelluloses and lignin to shrink more extensively in the transverse plane. During the drying process the microfibrils are drawn together laterally.

Consequently the shrinkage is different in the three principal directions, longitudinal, radial and tangential. Typical oven-dry shrinkage values are shown below, with heavier woods shrinking most:

Longitudinal shrinkage:	0.1 to 0.3%
Radial shrinkage:	2 to 6%
Tangential shrinkage:	5 to 10%

While the longitudinal shrinkage of a piece of wood is generally very small (0.1–0.3%), there are circumstances where it can be large. The theory of shrinkage has been described by Barber (1968) and Barber, Meylan (1964) and validated by Harris, Meylan (1965), Meylan (1968), Meylan, Cave (1972) and many others. These studies demonstrate that wood shrinks longitudinally (along the grain) by a significant amount only where the microfibril angle exceeds about 35° (Fig. 9). Further, the likelihood of a piece of wood warping depends on longitudinal shrinkage. High microfibril angles, and thus significant longitudinal shrinkage and warp, are usually found in the corewood, especially at the base of the tree (Fig. 6). The enlarged corewood zone of very low stiffness and short-fibers that is very prominent at the base of the tree can be

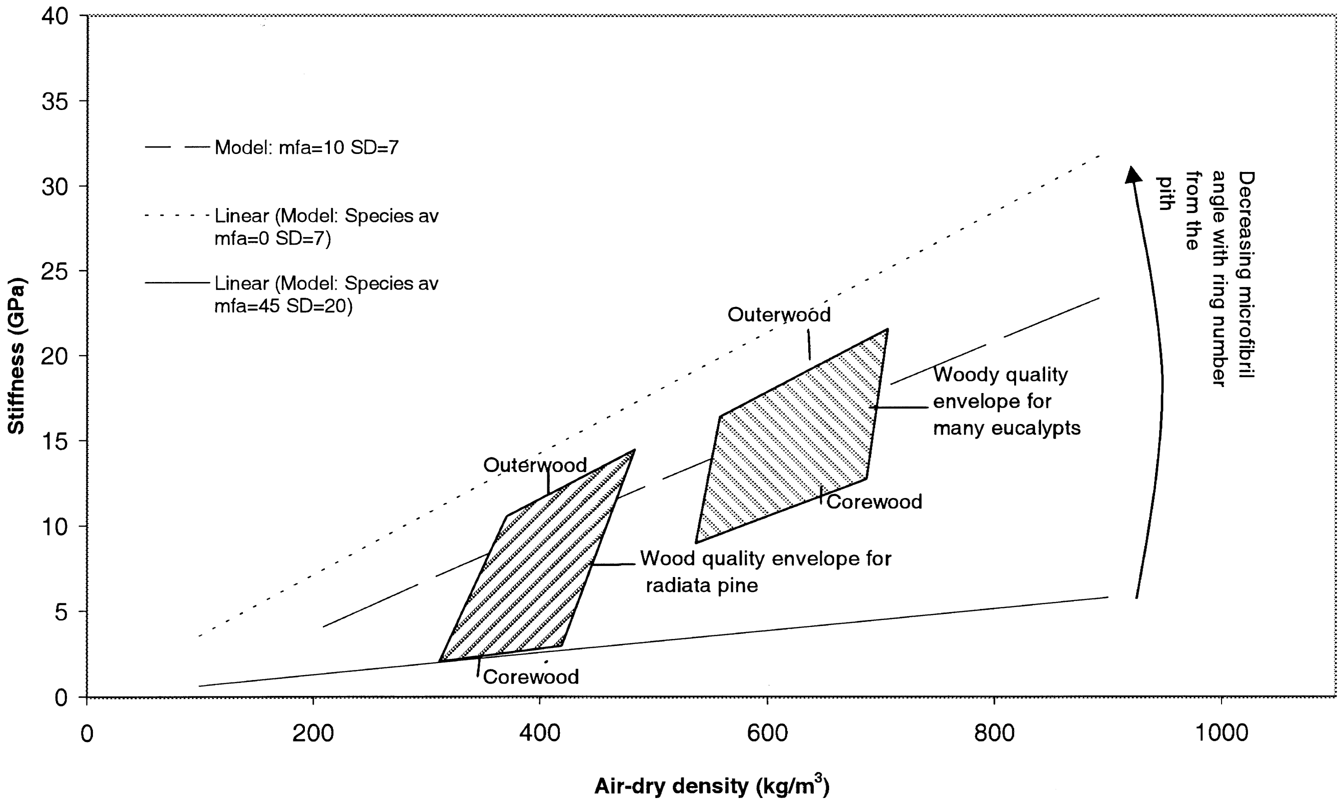

Fig. 8. Wood quality map incorporating the effects of density and cell wall ultrastructure for individual clearwood specimens of *Pinus radiata* and *Eucalyptus nitens*—within-tree data

Abb. 8. Karte der Holzqualität, den Dichteeinfluss und die Ultrastruktur der Zellwand für individuelle Reinholzproben von *Pinus radiata* und *Eucalyptus nitens* enthält—Daten innerhalb eines Baumes

isolated for mechanical pulp/fiberboard. Alternatively, the corewood could be cut into either flat-sawn thinboards, since any bow should be slight and easily corrected by restraint during drying, or large dimension material (300 × 75 or 200 × 50 mm in cross-section) that locates the pith centrally within the member (Maeglin, Boone 1983, Beauregard et al. 1992), or the corewood can simply be dried and finger-jointed to be corrected for warp. Density does not determine warp and instability. It merely magnifies the effects of intrinsic wood quality characteristics, whether good or bad. High-density corewood having the same microfibril angle as low-density corewood is less stable—it will shrink more during drying, amplifying any propensity of the wood to warp, and it will move more in service also by virtue of its higher density.

In practice the danger zone for excessive longitudinal shrinkage lies in the first 5–15 growth rings (Fig. 10). Bow (and crook) arise because of differences in the longitudinal shrinkage on opposite faces (or edges) of the board due to the different microfibril angles, e.g. a board having wood of ring 3 on one edge and ring 8 on the opposite edge could crook badly, with microfibril angles of 45° and 25°, respectively (Fig. 6; see also Fig. 11). Knowledge of the microfibril angles, the cross-sectional dimensions, and the stiffness should be sufficient to estimate a board's propensity to warp. That is, knowledge of the location within the tree from which the board had been sawn and the orientation of the growth-rings within the board indicate the manner and likelihood of warp. Outerwood is less prone to warp and instability, because the intrinsic wood quality of outerwood is far superior to that of corewood and not because it is of higher density. Occasional zones of compression wood in outerwood cause unexpected warp, since high density magnifies the effects of compression wood.

Clear differences between normal tracheids and cells with severe compression wood are revealed by the scanning electron microscope (Fig. 12). The cells are more rounded with intercellular spaces in the corners between the tracheids. Usually the S_3 layer is absent, while the S_2 layer has an outer highly-lignified zone and an inner less-lignified zone, in which there are ribs separated by deep helical cavities whose inclination correspond to that of the microfibrils (30–50°).

The longitudinal expansion of developing compression wood tracheids that occurs during cell lignification is the inverse of the longitudinal shrinkage that develops during kiln-drying (Boyd 1972, 1985). That is, during wood formation at the cambium; lignin deposition between the cellulose microfibrils in the secondary wall results in swelling transverse to the microfibrils. When the microfibril angle exceeds about 35°—and this is only likely in corewood wood and in compression wood—lignification will increase the cell length inducing compressive stresses on the underside of the leaning stem of softwoods. As the compression wood tracheids are laid down individually at the cambium, they expand very slightly longitudinally so that underside of the stem gradually builds up—cell-by-cell—the compressive leverage is necessary to correct the lean. The lean of even a large tree can be remedied over many years. In other words, the mechanism to straighten leaning stems also results in excessive longitudinal shrinkage and warp, when the timber is sawn and dried. In the latter case, the removal of moisture from the S_2 layer results in volumetric shrinkage and significant

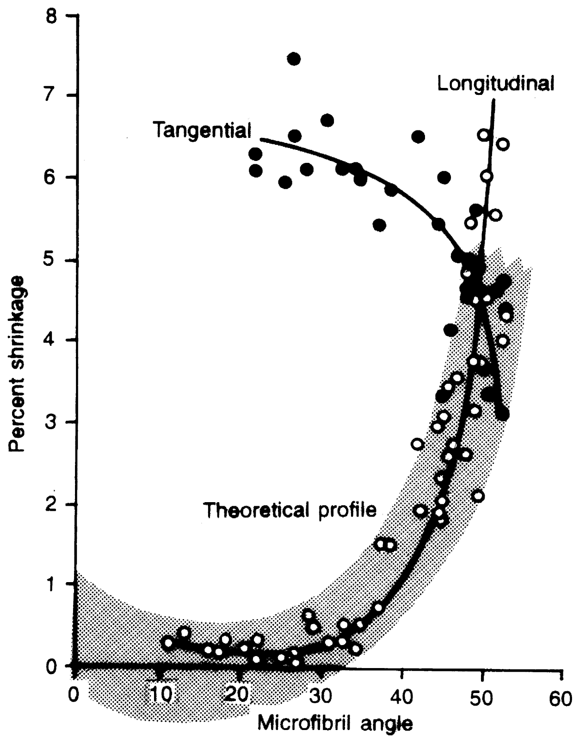

Fig. 9. Influence of microfibril angle on longitudinal shrinkage: experimental data for *Pinus jeffreyii* discs from breast height (after Meylan 1968), on which has been superimposed a band of theoretical profiles, depending on the stiffness and shear modulus of the cellulose and hemicelluloses-lignin matrix, respectively (adapted from Barber, Meylan 1964)
Abb. 9. Einfluss des Mikrofibrillenwinkels auf die Längsschrumpfung: experimentelle Daten für *Pinus jeffreyii* Scheiben in Brusthöhe (nach Meylan 1968), über das ein Band theoretischer Profile überlagert wurde, je nach Steifigkeit bzw. der Scherfestigkeit der Cellulosen- und Hemicellulosen-Lignin-Matrix. (angepasst nach Barber, Meylan 1964)

longitudinal shrinkage only when the microfibril angle exceeds about 35° (Fig. 9). The large microfibril angle in the S_2 layer means that the tracheids shrink excessively in the longitudinal direction during drying compared to normal wood (3–5% vs. 0.1–0.3%).

The formation of compression wood is not confined to obviously leaning trees. There is a high incidence near the pith of all softwoods, as the thin young stem is easily misaligned and seeks to straighten itself. Such instability or a wandering leader generates compression wood as the stem moves to counteract any stem wander. Overcorrection is frequently observed with arcs of compression wood forming on alternate sides of the stem: indeed very vigorous growth can produce mild compression wood in an annulus all around the stem, and the same effect has been noted after heavily thinning or fertilizing of stands. The result will be a formation of irregular arcs of compression wood within the stem meaning unpredictable distortion of individual boards.

4
Measuring wood properties with acoustics

Foresters are reluctant to consign large, nominally valuable sawlogs to the pulpmill as the price differential can be as high as 10:1 in favour of sawlogs. Yet, consider the proposition that 90% of all the problems in manufacturing good products can be attributed to 10% of the logs being milled. The unidentified poorest logs will be processed at a loss, because identification of poor quality is perceived only subsequently. Boards will be dried, only to warp unacceptably; structural lumber will be graded only to find that it fails to meet specifications. It would be negligent to sell such poor logs to sawmills once their intrinsic characteristics have been partially revealed, unless the poorest logs are identified and sold at a significant discount.

The processor is not primarily interested in obtaining superwood, but that as much of the wood supply as possible should meet some minimum threshold values for stability, stiffness and strength. This distinction is crucial. It switches interest from the superior qualities of the outerwood to the problematic issues of the corewood. It switches interest from identifying the best trees in a stand to knowing as much as possible about the poorest trees in

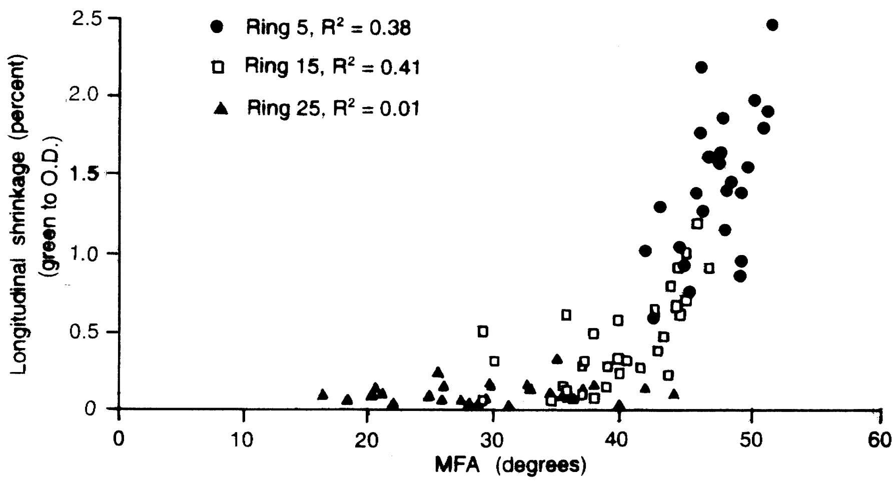

Fig. 10. Longitudinal shrinkage of loblolly pine as a function of microfibril angle for rings 5, 15 and 25 in butt samples of *Pinus taeda* (according to Megraw et al. 1998)
Abb. 10. Längsschrumpfung von Loblollykiefer als Funktion des Mikrofibrillenwinkels für die Ringe 5, 15 und 25 in Endstammproben von *Pinus taeda* (nach Megraw et al. 1998)

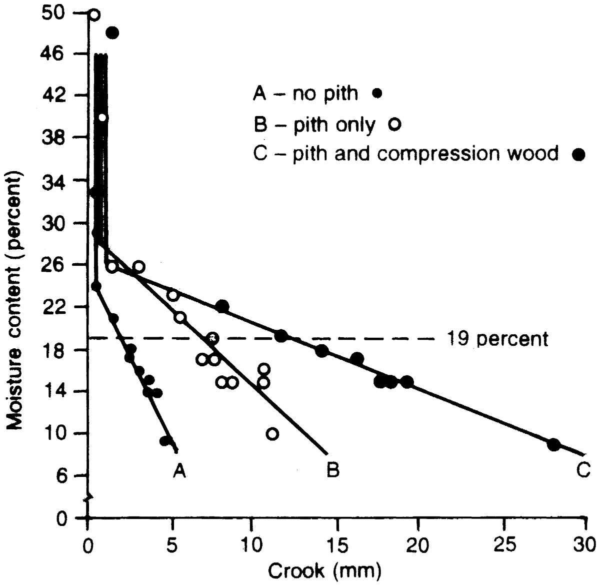

Fig. 11. Crook, arising from excessive shrinking along one edge of the board, is more prevalent in lumber cut to include the pith or with compression wood (modified from Gaby 1972)
Abb. 11. Eine Krümmung, die von exzessiver Schrumpfung entlang der Brettkante herrührt, ist häufiger in Schnittholz mit Mark und Druckholzanteilen vorhanden (modifiziert von Gaby 1972)

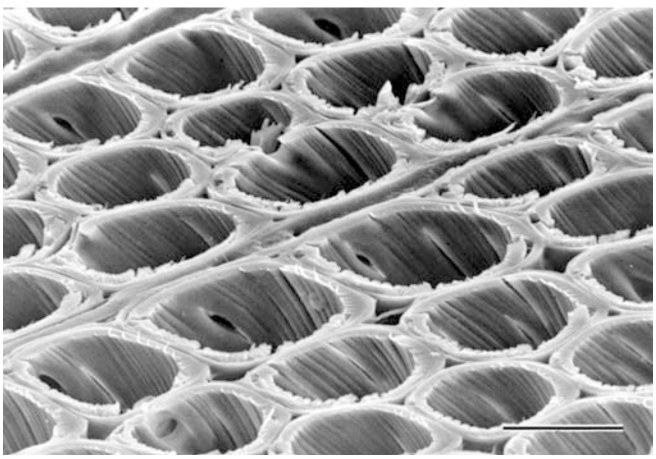

Fig. 12. Diagonal view of transverse face of compression wood of *Chamaecyparis obtusa.* Note that tracheids have a round shape in the cross-section, axial inter cellular spaces are highly developed and helical checks in the cell wall are clearly recognised. Scale bar = 20 micrometer
Abb. 12. Diagonaler Blick auf die Transversalfläche von Druckholz von *Chamaecyparis obtusa.* Tracheiden haben einen runden Querschnitt, axiale Interzellularräume sind hochentwickelt und helikale Risse in der Zellwand sind klar erkennen. Maßstab = 20 Mikrometer

a stand. It is critical, that the future of forestry lies in fast-grown plantations rather than in the natural forest, and that economic imperatives seek shorter rotations. Young plantations will contain a higher percentage of corewood thus creating a lower quality and more variable wood resource for industry to process (Kennedy 1995). Due to the large property variation in solid wood the future of the industry can be seen in engineered wood products where wood may be chipped, fiberised and blended before being glued together again: the average property values are little changed but the range—the variability—is greatly reduced. However, improved log sorting and tree breeding are examples of short- and long term possibilities to improve the product performance of solid wood products. Here the key to improvements lies in tools that measure and classify wood properties. Despite strong correlations between the microfibril angle and product performance, microfibril angle measurements, either by optical or X-ray diffraction-based methods (Preston 1974; Donaldson 1993; Lindström et al. 1998; Khalili 1999; Evans et al. 2001), are laboratory-based and of little practical assistance in the assessment of wood variability for industrial purposes. Fortunately, acoustic methods provide a fast, direct measurement of material stiffness, with the velocity of sound along a piece of wood being largely determined by the microfibrils: it is the averaged stiffness across the entire stem section that determines the velocity of sound along the log. The recorded acoustic velocity is an average value over the whole cross-section. In pines there is a stiffness gradient across the stem (Table 1).

At the same time the density of the "dry" freshly felled heartwood is roughly half that of green sapwood. These two effects compensate one another in such a way, that the velocity of sound in the outerwood is comparable to that in the corewood (V^2=MOE/ρ). This means that the axial stiffness can be derived directly from the velocity of sound, V. In practice companies need to measure only the velocity of sound, and rank/segregate logs into velocity groups using pre-determined cut-off velocities, in order to achieve "quasi-stiffness" sorts. This allows the forest owner to further segregate "identical logs" on the skid site or at the merchandising yard. The attraction of using acoustics lies in its simplicity.

Two interesting features arise from the use of acoustics. First, the fundamental equation, $MOE_{dynamic}=\rho V^2$, derives the axial stiffness directly from the velocity of sound, V, since the density of freshly felled wood, ρ, can be taken to be relatively constant, ca. 1000 kg m^{-3}. Secondly, this equation separates the contribution of density (wood quantity), which does not capture and reflect the characteristics counting for wood quality (Fig. 7). Granted, this equation ignores interactions; whereas in reality density and wood quality characteristics (such as the microfibril angle) are not entirely independent of one another, since both are age related.

Long- and short term possibilities The apparent ability to measure wood properties with acoustic tools can provide strategic information that can be used in harvesting and thinning operations to make better use of a given wood resource. For instance, sawmillers are aware of the considerable amount of variation in the intrinsic properties of logs, but do not have the means to recognise and so come to terms with it. The unidentifiable poorest logs have to be processed at a loss because identification of poor quality is revealed only subsequently. This variability exercises great pressure on process control operations and make it hard for sawmills to maintain existing standards. One solution would be to sort logs according to their intrinsic wood properties and thereby enable an optimal

Table 1. Mean modulus of elasticity (MOE) of *P. radiata* lumber based on relative distance from the pith (Addis Tsehaye et al. 2000)
Tabelle 1. Mittlerer Elastizitätsmodulus von Schnittholz (MOE) aus *P. radiata* basierend auf dem relativen Abstand vom Mark (Addis Tsehaye et al. 2000)

Source	A Nelson forest (60 trees)			A Canterbury forest (48 trees)		
Distance from pith	MOE (GPa)	Estimated green density (kg/m^3)	Estimated acoustic velocity (km/s)	MOE (GPa)	Estimated green density (kg/m^3)	Estimated acoustic velocity (km/s)
With-pith	6.3	550	3.4	5.0	550	3.0
25–50%	8.8	N/A	N/A	6.7	N/A	N/A
50–75%	11.9	N/A	N/A	8.5	N/A	N/A
Adjacent to the bark	15.1	1050	3.8	9.5	1050	3.0

Table 2. Mean modulus of elasticity of lumber cut from three groups of trees in two provinces of New Zealand ranked according to stiffness (Addis Tsehaye et al. 2000)
Tabelle 2. Mittlerer Elastizitätsmodulus von Schnittholz aus drei Baumgruppen in zwei Provinzen Neuseelands, nach Festigkeit sortiert (Addis Tsehaye et al. 2000)

Wood resource	A Nelson forest	A Canterbury forest
	The mean MOE (GPa) of lumber	The mean MOE (GPa) of lumber
Least stiff trees (poorest 10%)	6.9	4.7
Median stiffness trees: 80%	9.8	6.5
Stiffest trees (top 10%)	12.8	8.4

use of each log. Robust, field-based acoustic tools are being developed which are capable of sorting logs (harvesting), standing trees (tree selection when thinning a stand at middle age) and young seedlings (tree breeding) based on their stiffness. Working in the long time perspective, tree breeders could work within the broad genetic diversity inherent in trees to make their early selections from large, well-adapted populations of unrelated families or clones. Although much of the genetic potential to improve stiffness of juvenile wood seems to be a function of microfibril angle, this feature is difficult to measure and evaluate, and comparatively expensive. A more direct approach is to determine the acoustic stemwood MOE of young trees in order to identify candidates for future breeding programmes (Fujisawa 1998; Walker, Nakada 1999; Marchal, Jacques 1999; Lindström et al. in press).

4.1 Sorting saw logs through acoustics

Trees are amongst the most variable of all living organisms. There is an enormous range in wood properties within a pile of logs that has been sorted according to visible features, e.g. size and distribution of branches along the stem. This is even valid for logs from trees of the same age and from the same forest stand where the average stiffness of wood can vary by a factor of two (Table 2) due to a combination of micro-environmental conditions and genetic diversity.

Tapping a log (Harris, Andrews 1999) excites sonic waves in it that can be many metres long so knots are too small to perturb the signal and the stiffness measured is the average intrinsic quality of clear (knot-free) stem wood. Knots can be detected by probing in the ultrasonic region, but this is a different technique. With tapping, a better correspondence has been found between the acoustic velocity in the log and the average of all the local stiffnesses within the boards than by using the average of the local minimum stiffness within each board, which is governed primarily by the weakening effect of a large local knot. A US patent (US Patent 6,0026,689 2000), assignee Weyerhaeuser Company, demonstrates a significant correlation coefficient (R^2 = 0.64) between acoustic velocity along the log and the stiffness of lumber cut from that log for *Pinus taeda* in the Southern United States (Fig. 13). A value (R^2 = 0.46) derived from a sample of *Pinus radiata* logs is somewhat lower (Xu et al. 1999), but relates to logs of very variable small-end diameters, 90–480 mm. Both trials used stress wave timers so that better correlations were to be expected with the adoption of resonance techniques (Andrews 2000). Further, stress wave timers require a second worker at the other end of the log, which would be a safety issue on logging sites. Instead, the log end can be tapped with a hammer to launch a low-frequency sound wave that resonates up and down the log. The signal can be detected by using a microphone, or either by using an accelerometer or a piezoelectric transducer in contact with the log. Reverberations are quickly dampened in wet wood requiring antilogarithmic amplification of the signal to accurately measure the time lapse between repeated reflections at the same end of the log (Harris, Andrews 1999). Log taper and coupling between logs in a stack mean that the overtones are not strictly harmonic (Andrews 2000), *viz* the balance point is closer to the bottom than the top of the log.

In the first major study in New Zealand, 82 trees from a 27-year old stand of radiata pine were cut into four 4.2 m logs before being sorted by acoustics. Log stiffness, or rather velocity^2, was observed to vary by a factor of two or more, but perhaps unexpectedly there was little difference in average stiffness of logs on moving up the stem (Fig. 14). We attribute this to averaging within the stem section. The corewood at the base of the stem is significantly less stiff than elsewhere in the tree, but the butt log has also both more and stiffer outerwood to compensate;

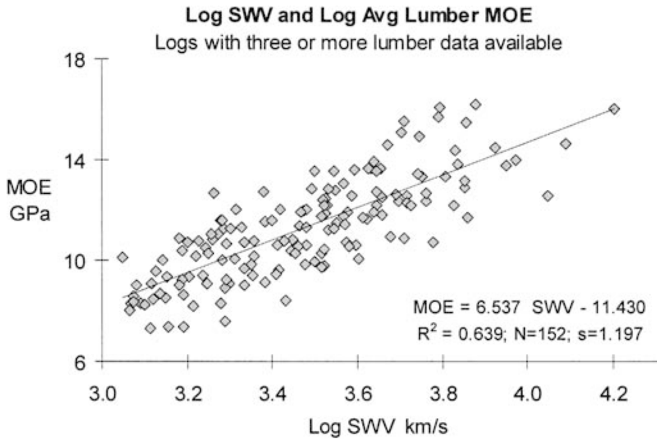

Fig. 13. Comparison between the velocity of sound along a loblolly pine (*Pinus taeda*) log and the stiffness of the wood in that log (after US Patent 6,026,689)
Abb. 13. Vergleich zwischen der Schallgeschwindigkeit entlang eines Loblollykiefer (*Pinus taeda*) Rundholzes und der Steifigkeit des Holzes in diesem Rundholz (nach US-Patent 6,026,689)

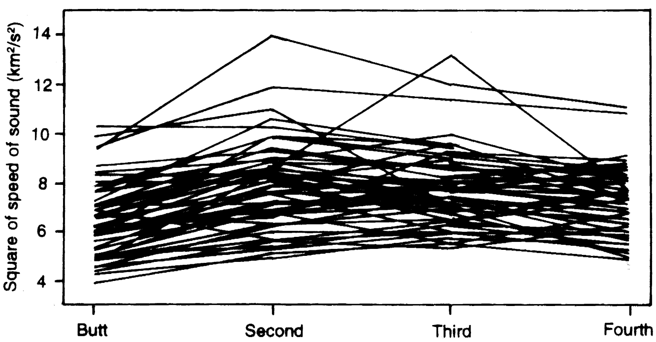

Fig. 14. Square of velocity of sound, V^2, for all logs from 82 trees from an unpruned stand of *Pinus radiata* (according to Xu et al. 1999)
Abb. 14. Quadrat der Schallgeschwindigkeit, V^2, für alle Balken von 82 Bäumen eines ungeästeten Bestands von *Pinus radiata* (nach Xu et al. 1999)

whereas at the top of the stem the corewood is somewhat stiffer, but there is only a little outerwood of moderate stiffness (Fig. 17). In this study, (Addis Tsehaye et al. 2000), no thought has been given to measuring the velocity of sound along the entire stem prior to cross-cutting. However, stems could be ranked retrospectively by averaging the velocity of sound for all four 4.2 m logs from each stem. Three-quarters of the poorest logs (the 25% of logs displaying the lowest acoustic velocities in each category, e.g. butt, middle, top and upper-top logs) came from the same stems. This implies that one can cut various log lengths and produce a number of log categories on the basis of whole-stem acoustic data. Traditionally, stems are cut into 4.2–6.1 m sawlogs, with the large butt log commanding a premium as it yields a higher recovery (m^3 of sawn wood per m^3 of log) and a high volume output per lineal metre of log input (increased productivity). However, the very poor stiffness of corewood in the bottom three metres of the stem (Fig. 15) in fast-growing plantation softwoods has not been recognised by sawmillers and

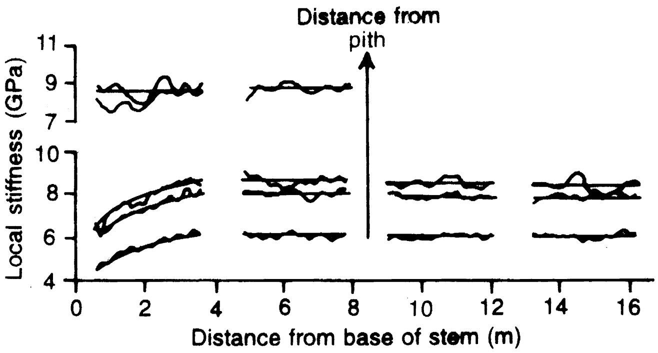

Fig. 15. Radial and axial variations in the mean local bending stiffness of sawn lumber cut from the same logs as in Fig. 13 (according to Xu and Walker, in press)
Abb. 15. Radiale und axiale Variationen in der mittleren lokalen Biegesteifigkeit von Schnittholz, aus dem gleichen Rundholz wie in Abb. 13 (nach Xu und Walker, im Druck)

is an unsuspected observation to arise from this acoustic work. It is suggested, that a short 2.4 m butt log might be cut and then subsequent logs would have annuli of uniform stiffness, thus making milling more efficient. The stiff outerwood of the short butt log would be ideal for peeling (plywood/laminated veneer lumber) or for structural lumber.

Acoustic sorting allows the forest owner to select populations of premium logs for structural mills that require high stiffness wood. The benefits, in terms of improved stiffness, achieved either by isolating the poorest logs (ca. 20%) that could be processed into non-structural products or by selecting the best wood (ca. 30%) for superior structural grades are illustrated in Figs. 16 and 17. The benefit of acoustic log sorting is immediately obvious in case of the high velocity logs producing stiffer wood. Revenue optimisation will determine the appropriate log acoustic velocity cut-off points: these will depend on the wood resource being milled and the desired end products. In this study 350 logs produced 2088 boards and 52308 individual stiffness values (recorded at 150-mm intervals along the boards by a machine stress grader). The individual stiffness values (footprints) along the boards have been plotted for each of the three log-velocity sorts (Fig. 16). This is relevant for finger-jointing, remanufacturing or laminating where only the worst defect(s) is (are) cut from the board so that all remaining values along the board are important. In Fig. 17 only the single lowest individual stiffness value (the least stiff footprint) for each board in each of the log-velocity sorts has been plotted. Structural grading focuses on the least stiff/weakest point along the board, which generally corresponds to the location of the largest knot. Therefore, Fig. 17 relates well using board strength, because the largest knot defects are reasonable predictors of board strength. However, this procedure underestimates the average board stiffness which is the significant value in much timber design, and it also results in a poorer recovery of better grades of timber (Fig. 17 vs. Fig. 16).

The general problem of warp in butt logs has long been recognized (Cockrell 1943), "*In butt logs, the combination of high longitudinal shrinkage near the pith and slight*

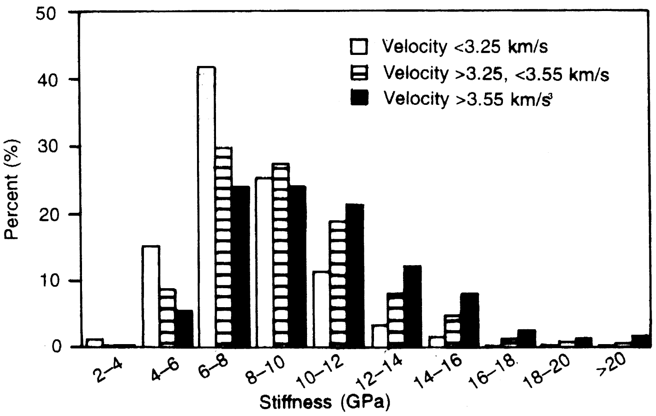

Fig. 16. Grouping logs of *Pinus radiata* into three velocity sorts results in three distinctive sawn lumber outputs. In this Figure the populations are represented in terms of the individual footprints, the grade values recorded at 150-mm intervals along the board, which is relevant for finger-jointing and remanufacturing industries

Abb. 16. Sortieren von Kiefernrundholz von *Pinus radiata* in drei Geschwindigkeitsklassen ergibt drei unterschiedliche Schnittholzgruppen. In diesem Bild werden die Populationen mittels individueller Kennzeichen dargestellt. Die Werte wurden in 150 mm Schritten entlang des Brettes gemessen, die für Kleinzinkverbindungen und die weiterverarbeitende Industrie von Bedeutung sind

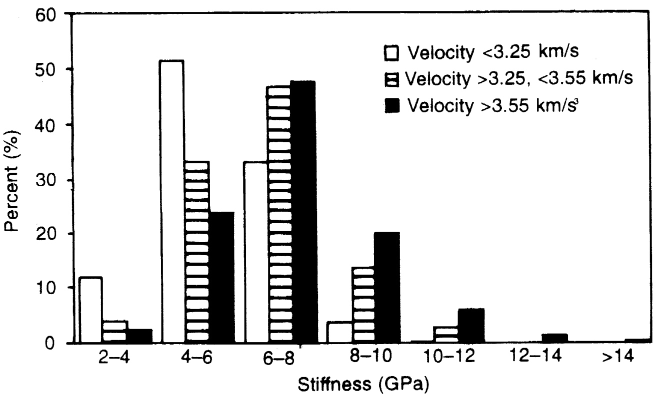

Fig. 17. Grouping logs into three velocity sorts results in three distinctive sawn lumber outputs. In this figure the populations are defined in terms of the poorest grade value (GPa) along the board, which value is used for the grading of structural lumber

Abb. 17. Sortieren von Kiefernrundholz von *Pinus radiata* in drei Geschwindigkeitsklassen ergibt drei unterschiedliche Schnittholzgruppen. Auf diesem Bild werden die Populationen durch den geringsten Wert, der zum Sortieren des Bauholzes verwendet wird, definiert

shrinkage or elongation of the wood further out [sic] can... result in pronounced warping [crook] of boards cut with one edge along the pith. ...no lumber can be safely cut with the pith on one edge without increasing the risk of degrade in seasoning. It would, therefore, be good practice to saw logs, and especially butt logs, so that the pith is approximately in the center of the board or timber". Sawmillers may be reluctant to cut short butt logs from all stems. In that case, acoustics provides a tool to identify the most problematic butt logs. Only, the slowest velocity tail of the population—the slowest 10–20% of stems—could be

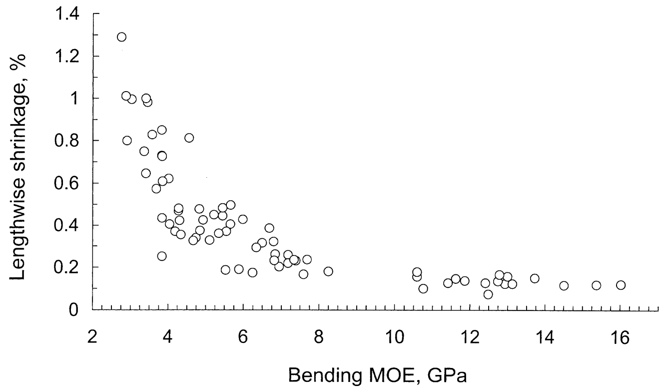

Fig. 18. Longitudinal shrinkage increases dramatically in very low stiffness loblolly pine boards (after International Patent WO 00/12230)

Abb. 18. Längsschrumpfung erhöht sich dramatisch in Brettern aus Loblollykiefer mit sehr niedriger Steifigkeit (nach Internationalem Patent WO°00/12230)

processed separately to give short butt logs as the effects of warp and low stiffness will be magnified greatly in these logs.

Weyerhaeuser (International Patent WO 00/12230) has shown excellent non-linear relationships between stiffness and longitudinal shrinkage in lumber (Fig. 18), which mirror those for microfibril angle (Fig. 9). However, because a longitudinal shrinkage *gradient* across a board is necessary to induce warp, average values for boards are of little relevance. Hence the patent indicates that *multiple* measurements of some complexity are needed to identify warp-prone boards. Similarly, Weyerhaeuser (Megraw et al. 1998) has observed that noticeable longitudinal shrinkage in discs cut from logs parallels the production of more warp-prone lumber from those logs (Fig. 19). The greater warp in the loblolly pine butt logs mirrors the very low stiffness observed in corewood of radiata pine butt logs (Fig. 15). But identification and warp potential still remains problematic.

4.2
Sorting pulp logs through acoustics

Fiber length is an important characteristic for papermaking. Echols (1955) found that tracheid length accounted for 91% of the variation in microfibril angle in *Pinus elliottii*. Although Echols's correlation is so large that it would not matter greatly, if tracheid length was taken as a surrogate measure for microfibril angle (or vice versa), poorer correlations appear in the literature. For example, Hirakawa and Fujisawa (1995) obtained a more modest correlation coefficient (r^2=0.48) in a detailed study of latewood tracheids of *Cryptomeria japonica* (Fig. 20). Still, the relationship between microfibril angle and tracheid length encouraged an alternative approach of determining microfibril angles, $\theta°$ indirectly by measuring tracheid length, L (Preston 1974). Two statistical equations have been advocated, $L=a+b\text{Cot}\theta$ and $L=a-b\theta$.

As the sound velocity in wood is dependent on the microfibril angle, the relatively strong relationship found between tracheid length and microfibril angle (Echols 1955, Preston 1974, Hirikawa, Fujisawa 1995) indicate that

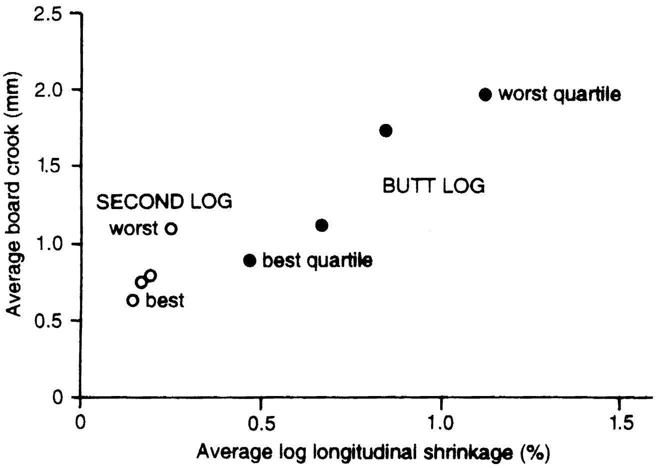

Fig. 19. Average log longitudinal shrinkage, by quartile, plotted against average board crook for boards coming from logs in that quartile (according to Megraw et al. 1998). Log shrinkage values were obtained from discs cut from the large end of each log
Abb. 19. Durchschnittliche Rundholz-Längsschrumpfung, als Quartilen aufgetragen gegen die durchschnittliche Brettkrümmung, die von Rundholz in diesem Quartil stammt (nach Megraw et al. 1998). Werte der Rundholzschrumpfung wurden von Holzscheiben erhalten, die vom dickeren Ende jedes Rundholzes geschnitten wurden

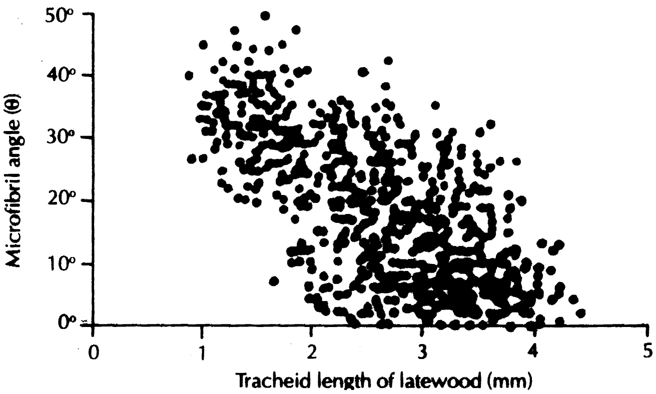

Fig. 20. Tracheid lengths and microfibril angles for macerated latewood tracheids of six clones using tissue from the 2nd, 6th, 16th and 20th growth rings (after Hirakawa, Fujisawa 1995)
Abb. 20. Tracheidenlängen und Mikrofibrillenwinkel für mazerierte Spätholztracheiden von sechs Klonen; verwendetes Gewebe von den 2., 6., 16. und 20. Jahresringen (nach Hirakawa, Fujisawa 1995)

sound velocity could be used to sort pulp logs by fiber length. The first trial used 250 radiata pine peeler cores (Albert et al. in press). These were the 149–189 mm diameter cores remaining once the 2.4 m bolts/logs had been rotary-peeled for veneer; at which point the cores are rejected from the veneer lathe. In New Zealand, peeler logs come from large-diameter butt logs, so the cores would be expected to contain very low-stiffness wood with short fibers (Fig. 15). The velocity of sound was measured along each peeler core, which were then ranked and segregated into 18 velocity of sound sorts. Discs were taken from both ends of the peeler cores for subsequent measurement of key pulp and paper properties. The pairs of discs were

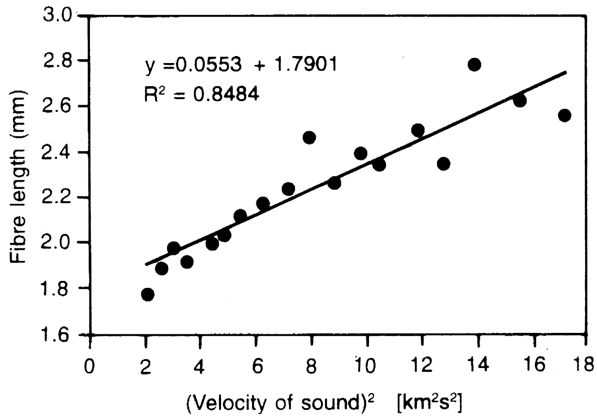

Fig. 21. Length-weighted average fiber length against the stress wave velocity in the logs (after NZ Patent 331527 1999)
Abb. 21. Längengewichtete Durchschnittsfaserlänge, aufgetragen gegen die Spannungswellengeschwindigkeit ins Rundholz (nach NZ Patent 331527 1999)

grouped into the 18 sound velocity sorts, chipped and pulped by the Kraft process. The large variation in both length-weighted average fiber length (Fig. 21) and pulp strength across the 18 sound velocity sorts is highly significant, as hitherto corewood has been treated—by default—as reasonably homogeneous in relation to fiber quality. For example, the stiffest, high acoustic velocity sorts (Fig. 21) would normally be associated with high-density, long-fibered material from the outerwood, while the least-stiff sorts contained very short fibers, even shorter than it would normally be associated with corewood. A second trial with 250 industrial pulp logs with large-end diameters ranging from 120–420 mm yielded similar results (Clark et al. in press). Hitherto, sorting pulpwood for fitness of purpose has been limited to segregation between corewood (top-logs or young forest thinnings) and outerwood (the rounded slabs/edgings arising from sawmilling). Long, strong fibers are highly desirable for fiber-cement pulp. These have traditionally come from high-density outerwood. At the other extreme, the shortest, thin-walled fibers can be beaten to give high-density (low-porosity) papers, e.g. quick release and glassine. These have come from corewood. However, acoustics means that individual logs can be allocated across the spectrum of paper products: some forest thinning might be used for mechanical pulp or writing grade paper; some outer slabwood might be more suitable as fluff pulp or packing grade paper.

5 Conclusions

Fundamental wood quality research over the last 65 years identified the cellulose microfibril angle in wood cells to be the most significant characteristic controlling wood properties of fast-grown softwoods. However, the use of x-ray diffraction for quality control in the forest and sawmill is impractical. Opportunities arose only when it was realised that low-frequency sound correlated with log stiffness and thus provided a surrogate tool. Low-cost, field-hardened acoustic tools have been developed for the forest industries over the last decade. Acoustic methods are efficient non-destructive tools for sorting forest raw materials. The opportunity lies in the ability to characterize individual logs rather than treating "visually similar logs" as a broad population. It has been shown, that acoustic methods can grade sawlogs according to their suitability for structural lumber and can sort pulp logs according to fibre length for paper grades. This is significant, as similar logs can have wood/fiber characteristics and properties that differ by at least a factor of two. In the longer time perspective, there are substantial benefits in using acoustics in tree breeding to screen for candidate trees with superior wood properties.

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