# PRIOR LAND-USE INFLUENCES WOOD PROPERTIES OF *PINUS RADIATA* IN NEW SOUTH WALES

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## ABSTRACT

Three pairs of sites in the Oberon area of NSW were sampled to determine the effect of prior land-use (pasture or plantation) on a range of wood properties for *Pinus radiata* D. Don. Paired sites were matched as closely as possible for climate and soil type. Ten trees at each site were sampled at ages 19 or 20, and outerwood basic density, fibre length, fibre coarseness, and wood pH were determined using breast-height cores. In addition, pith-to-bark profiles for air-dry density and microfibril angle were mapped for each sample.

Consistent differences in wood and fibre properties were found between the paired ex-pasture and second-rotation sites. Overall, the ex-pasture sites produced lower-density wood with shorter fibres, lower fibre coarseness, higher pH, and higher microfibril angle leading to a decrease in calculated modulus of elasticity. However, when results were examined across all pairs of sites, large differences were also apparent within forest areas, with some ex-pasture sites producing better-quality wood than some second-rotation sites.

Despite differences in growth patterns with prior land-use, the age of change from juvenile to mature-type wood was the same for the two site types. In the growth rings closest to the pith, wood density was similar for the ex-pasture and second-rotation sites. However, from Ring 6 onwards density was consistently higher for the second-rotation sites. There was little effect of site type on patterns of change for microfibril angle. The major effect of site type would appear to come from an increase in the volume of juvenile corewood on the ex-pasture sites.

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## INTRODUCTION

As the pine plantation resource in NSW has expanded from the traditional higher-elevation forest areas on to ex-farm country, the planting sites have encompassed a wider range of prior land-uses. Many of the newer plantations have been established on ex-pasture country, which has had its nutrient status improved by regular fertiliser application or by the sowing of legumes. In addition, some of the traditional forest areas are producing second-rotation (2R) crops that are now of an age when limited harvesting is commencing, based on first or second thinnings. It could be expected that there would be a difference in the fertility of ex-pasture and second-rotation sites given their prior land-use history. Differences in tree growth and form are apparent between land-use classes (Birk 1992, 1993), but little is known about the potential differences in the wood quality of these trees.

Wood properties of *Pinus radiata* change from pith to bark as the cambial age at the time of wood formation increases (Harris 1981). Ring averages for wood density, tracheid length, fibre coarseness, and cellulose content all increase from pith to bark, and microfibril angle and lignin content decrease with distance from the pith (Cown 1980, 1992a,b; Donaldson 1992; Uprichard & Lloyd 1980). These changes give rise to a central region of less-desirable corewood which is characterised by wider growth rings, lower wood density, high longitudinal shrinkage, high spiral grain angles, and shorter tracheids. Cown (1992a) defined the corewood zone of juvenile wood as the inner 10 growth rings.

Differences in tree growth patterns, induced by different prior land-uses, could be expected to lead to differences in the amounts of juvenile corewood being produced. If trees on ex-pasture sites are growing at a faster rate initially, a greater volume of corewood should be produced. A related issue is whether the change from juvenile to a more mature form of wood is predetermined by tree age or can be altered by growth rate. The third issue of interest is the effect of land use *per se* on the type of wood being produced at any given age. Each of these issues was addressed in our study.

A range of potential markets is available for the current crop, with possible options including sawn timber, peeled veneer, kraft or thermomechanical pulp and paper, particleboard, or medium-density fibreboard (MDF). As each product has different requirements and thresholds for acceptable wood quality, a wide range of wood properties was included in the current study. Properties assessed included density, fibre length and coarseness, microfibril angle, modulus of elasticity, pH, and acoustic velocity.

Basic density is a critical timber quality trait for the production of pulp, paper, and sawn timber (Zobel & van Buijtenen 1989). Fibre length and fibre coarseness are important for manufacture of pulp and paper and medium-density fibreboard. Fibre length influences paper strength, particularly tear, and paper machine runnability (Watson & Dadswell 1961; Jackson 1988); fibre coarseness, the mass of oven-dry material per unit length of fibre, is related to the ability of a fibre to collapse in a sheet of paper or medium-density fibreboard. Assuming constant fibre diameter, coarser fibres generally have thicker cell walls, are stiffer and more inflexible, resist collapse and, therefore, form bulkier, more porous, and rougher sheets. Microfibril angle refers to the orientation of the cellulose fibrils in the S2 layer of the cell wall — the lower the angle, the stiffer the individual fibre and the piece of wood. Wood pH is important for any products requiring glueing such as veneers, particleboard, or medium-density fibreboard as it can affect the curability of the resins used. Acidic extractives also consume the alkali required for lignin cleavage and removal during kraft pulping (Uprichard & Lloyd 1980). The velocity of sound in wood is related to wood stiffness (Walker & Nakada 1999) and fibre length (Albert *et al.* 2002). Measurement of acoustic velocity is simple and rapid and, if the correlations are sufficiently large, offers a cost-effective method for assessing these traits.

Each of these wood properties is influenced by many factors including genotype, tree age, climate, and growing conditions. To determine the influence of any of these alone, it is desirable to limit the variability in other factors. So, to examine whether consistent differences exist between prior land-use classes, this study sampled trees that originated from the same seed source and nursery and were planted in the same year. The study aimed to provide initial information on variability in a range of wood properties for a single age-class across a range of site qualities and two previous land-uses (plantation and pasture). The selected sampling sites were within a limited geographic range to minimise climatic variability and on the same soil type where possible. This project was funded jointly by Forests NSW and the Central Western Regional Development Board, through the Regional Plantation Committee, and aimed to develop a better understanding of the wood characteristics of the region to enable more efficient processing and to improve efficiencies within the plantation forestry sector (URS Forestry 2001).

## MATERIALS AND METHODS

### Field Sampling

Three pairs of sites were sampled in the Oberon area of NSW, with the ex-pasture and second-rotation sites matched as closely as possible for age and soil type. Trees were 19 or 20 years old when sampled (*see* Table 1 for age-class), and all trees were from the same seed source and nursery. Gurnang and Vulcan Forests are both south

TABLE 1–Site location information

| Site | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Forest | Gurnang | Gurnang | Gurnang | Gurnang | Vulcan | Vulcan |
| Compartment | 380 | 20 | 385 | 27 | 458 | 17 |
| Age class (year est.) | 1983 | 1983 | 1984 | 1984 | 1983 | 1983 |
| Latitude (°S) | 33 55 | 34 01 | 33 58 | 34 01 | 33 51 | 33 54 |
| Longitude (°E) | 149 53 | 149 51 | 149 58 | 149 51 | 149 47 | 149 41 |
| Altitude (m a.s.l.) | 1200 | 1200 | 1200 | 1210 | 1200 | 1135 |
| Parent rock code* | 5 | 5 | 5 | 5 | 8 | 9 |
| Previous land-use† | Pasture | 2R | Pasture | 2R | Pasture | 2R |
| Initial stocking (stems/ha) | 985 | 992 | 1456 | 1180 | 900 | 989 |
| Thinning status | Unthinned | Unthinned | Unthinned | Unthinned | Thinned 1998 to 168 stems /ha | Thinned 1999 to 400 stems /ha |

* Parent Rock code from Turner *et al.* (1996)
Code 5 is argillaceous group including slates, shales, mudstones, greywacke
Code 8 is feldspathic-quartise group including rhyolite
Code 9 is feldspathic-micaceous group including grandiorite

† 2R = second-rotation

of Oberon, with Vulcan to the west of Gurnang. The average annual rainfall for this area is approximately 950 mm. At each site 10 trees were selected as being straight, unforked, without visible defects, and representative of the site. Each tree was measured for diameter over bark at 1.3 m (dbh); it was then hand felled and delimbed, and total tree height was measured. A 5-m butt log was cut from each tree, and acoustic velocity for each log was measured using a Director HM200 acoustic tool.

From each tree four, 12-mm-diameter, bark-to-bark, wood cores were collected, one above the other, at around 1.3 m above ground. One core was used for measuring outerwood basic density in the manner that it is routinely assessed (using the outer five rings), one for assessing pith-to-bark profiles for density and microfibril angle using SilviScan (Downes *et al.* 1997: Evans *et al.* 2000), one for fibre length and coarseness, and a fourth core for wood pH. Each core was labelled with site and tree identification, wrapped in plastic, and kept cool before being despatched for processing.

## Assessment of Wood and Fibre Properties

Outerwood basic density (outer five rings), defined as oven-dry mass divided by green volume, was determined on one core sample from each tree, using the maximum moisture content method (Smith 1954). The second core was used for assessing air-dry density and microfibril angle via X-ray densitometry and diffraction using SilviScan. These cores were placed in ethanol, and all water in the core was replaced with ethanol prior to drying with the aim of minimising cell collapse due to hydrostatic tension during the drying process. Once air-dry, these cores were prepared and a single radius per sample was analysed by SilviScan to measure pith-to-bark air-dry density (air-dry mass divided by air-dry volume) and microfibril angle (the angle of orientation of the cellulose microfibrils to the longitudinal axis of the fibre). High-resolution radial density profiles were obtained for each radius. Microfibril angle profiles were obtained as 5-mm averages across each radius.

The other two cores from each tree were air-dried in a constant temperature and humidity room (23°C, 50% RH) and then processed to determine fibre length, fibre coarseness, and wood pH. One core from each tree was split longitudinally across the grain to produce two half cores from bark to bark. Any evidence of bark was removed from the core. Half of each core was enclosed in a numbered wire mesh basket and batches of cores were placed in a pulping autoclave and subjected to laboratory kraft pulping. The other half core was stored as a backup sample. Laboratory pulping was undertaken using a Haato 12 autoclave air pulping digester and associated equipment to delignify and separate the fibres within each core sample. Pulping conditions were as follows:

| | |
|---|---|
| Cook temperature | 170°C |
| Activation energy | 145.7 kJ/mole |
| Target 'H' factor | 2865 |
| Nominal time to temperature | 90 minutes* |
| Nominal time at temperature | 90 minutes* |
| Sulphidity | 25% |
| Liquor ratio | 5:1 |
| Active alkali (%NAOH on o.d. wood) | 23.7% |

After pulping, each sample basket was allowed to soak in water to remove free cooking liquor and lignin for about 1 hour. Each half core was removed from the basket and the outer edge was removed to eliminate the majority of cut fibres. The half cores were then disintegrated in a Waring Blender for a few seconds on low speed to disperse the fibres. A stock concentration was determined on each sample following the principle outlined in AS/NZS1301.207 to give an accurate oven-dried fibre content for Kajaani FS200 fibre length and coarseness.

Each half core sample was then run through the Kajaani FS200 in duplicate to determine fibre length and coarseness. The Kajaani measures the length of thousands of fibres from each sample using optic measurement on fibres as they pass through a fine capillary. Length-weighted average fibre length and fibre

* Actual times are controlled by the 'H' factor

coarseness were determined. Length-weighted averages were used as these reduce the influence of cut and broken fibres by placing greater emphasis on the longer whole fibres. Fibre coarseness is defined as the mass of oven-dry material per unit length of fibre. Coarseness, as determined by the FS200, does not provide information on fibre diameter or wall thickness unless one of these is considered to be a constant. Fibres with the same coarseness value may have either large diameters with thin walls or small diameters with thick walls.

The second air-dried core from each tree was broken into pieces 25 to 35 mm long prior to testing for pH. Duplicate samples were boiled in water for 1 hour, and pH was determined from measurement of the cooking liquid.

## Data Analysis

Data for duplicates for outerwood density, fibre length, fibre coarseness, and pH were averaged to give a single value per tree and collated with the growth and acoustic data.

The X-ray diffraction and density data from SilviScan were used to calculate a radial profile for acoustic modulus of elasticity ($MOE_{SS}$, representing SilviScan MOE) (Evans & Ilic 2001). The high-resolution radial density profiles, $MOE_{SS}$, and microfibril angle profiles were analysed in several ways. Firstly, an average value was obtained for each tree based on the area weighted mean value — each data point in the pith-to-bark profile was weighted by the cross-sectional area represented by that point. Secondly, the density traces were used to allocate annual ring boundaries across each core, with each annual ring demarcated by the change from high-density latewood, formed at the end of the growing season, to low-density earlywood, formed at the beginning of the next growing season. The locations of each ring boundary were then used to calculate ring widths (representing diameter growth) and ring-by-ring averages for air-dry density, microfibril angle, and $MOE_{SS}$ for each tree. The annual ring data for diameter growth and the wood properties were collated for each site, and site averages were determined for patterns of change for each trait from pith to bark. Polynomial regression equations were fitted to the microfibril angle and $MOE_{SS}$ data and tested to determine whether the regression lines were parallel across each pair of sites.

Individual tree data were analysed to determine whether there was a consistent difference between prior land-use across each of the three paired site groupings. The model fitted contained terms for group, prior land-use (PLU) nested within group, and the residual error. The individual tree data were also used to determine the correlations between traits for each site. Pith-to-bark patterns of change for diameter, air-dry density, microfibril angle, and $MOE_{SS}$ were plotted for each matched pair of sample sites to determine whether the patterns of change were consistent and whether the age of change from juvenile to mature wood was constant or was affected by site type. Finally, the value of the acoustic velocity data obtained from the Director HM200 was determined by examining the regression relationships between acoustic velocity on the butt logs with fibre length, microfibril angle, and $MOE_{ss}$.

## RESULTS

### Analyses of Variance

Results of the analyses of variance for each trait are presented in Table 2. Significant differences were found between the groups for all traits, with the exception of fibre coarseness. Within each group, the effect of prior land-use was significant for all traits examined.

TABLE 2–Results of analyses of variance for each trait

| Trait/Source | DF | MS | Signif. | Trait/Source | DF | MS | Signif. |
|---|---|---|---|---|---|---|---|
| Diameter | | | | Acoustic velocity | | | |
| Group | 2 | 311.2 | ** | Group | 2 | 0.668 | ** |
| PLU† | 3 | 46.2 | * | PLU | 3 | 0.104 | * |
| Error | 54 | 11.3 | | Error | 54 | 0.031 | |
| Height | | | | Airdry density | | | |
| Group | 2 | 27.5 | ** | Group | 2 | 9370 | ** |
| PLU | 3 | 13.2 | ** | PLU | 3 | 5165 | * |
| Error | 54 | 1.9 | | Error | 54 | 1363 | |
| Basic density | | | | Microfibril angle | | | |
| Group | 2 | 15473 | ** | Group | 2 | 99.7 | ** |
| PLU | 3 | 4867 | ** | PLU | 3 | 37.5 | ** |
| Error | 54 | 965 | | Error | 54 | 8.9 | |
| Fibre length | | | | $MOE_{ss}$ | | | |
| Group | 2 | 0.185 | ** | Group | 2 | 43.2 | ** |
| PLU | 3 | 0.077 | * | PLU | 3 | 25.4 | ** |
| Error | 54 | 0.020 | | Error | 54 | 3.4 | |
| Fibre coarseness | | | | pH | | | |
| Group | 2 | 11.25 | ns | Group | 2 | 0.246 | ** |
| PLU | 3 | 42.74 | ** | PLU | 3 | 0.221 | ** |
| Error | 54 | 7.24 | | Error | 54 | 0.020 | |

** significant at p<0.01
* significant at p<0.05
ns not significant
† PLU = previous land-use

### Site Means

Site means for each trait (Fig. 1) indicate that, although there were differences between the pair groupings, the differences between prior land-use classes were

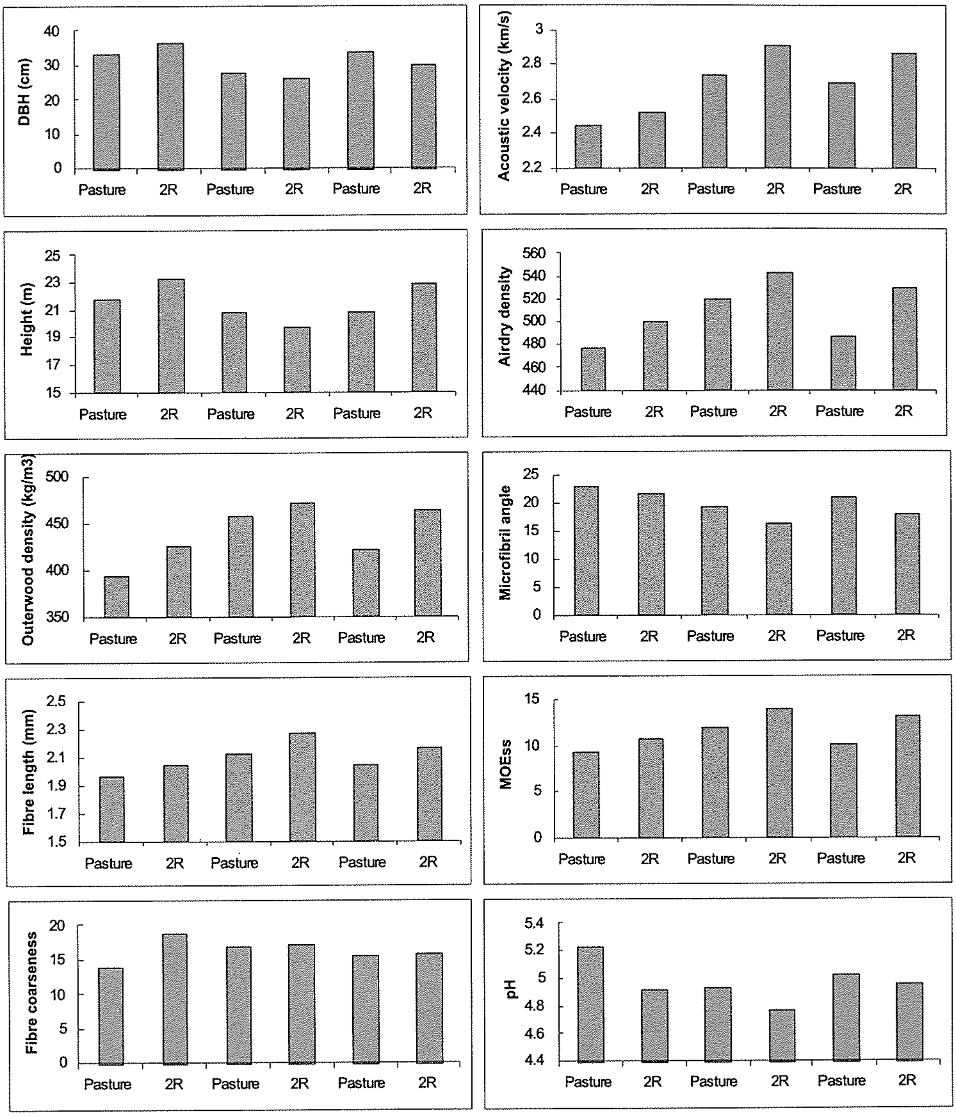


FIG. 1–Site means for each trait. Site 1 is on the left and Site 6 on the right.

consistent for each pair of sites. Overall, the ex-pasture sites were 6% lower for density, and had shorter fibres (5%) with lower fibre coarseness (11% lower), higher pH (3.7%), and higher microfibril angle (14% higher), leading to a 16% decrease in calculated modulus of elasticity ($MOE_{ss}$).

However, when results were examined across all pairs of sites, large differences were also apparent within forest areas, with some ex-pasture sites producing better-quality wood than some of the second-rotation sites. Sites 1 to 4 all occurred relatively close together within Gurnang Forest, were on the same soil type, were at the same altitude, and would have very similar climates. Within this group, Site 3 (an ex-pasture site) produced better quality wood than Site 2 (second-rotation) with higher density, longer fibres, lower microfibril angle, and higher $MOE_{ss}$. Sites 1 and 2 produced the lowest quality wood of all the tested sites, even though these sites differed in prior land-use.

## Growth Patterns

Pith-to-bark growth patterns (Fig. 2) indicated that there were differences in patterns of growth between the ex-pasture and second-rotation sites but these differences were not always in the expected direction. For Sites 1 and 2 the second-rotation site grew at a faster rate than the ex-pasture site from Ring 3 onwards. For Sites 3 and 4, the final tree diameters were very similar although the growth patterns appeared to differ with the ex-pasture site initially growing faster, but after Ring 8 the second-rotation site showed the greater ring width. Sites 5 and 6 appeared to have very different growth patterns with the ex-pasture site growing rapidly for the

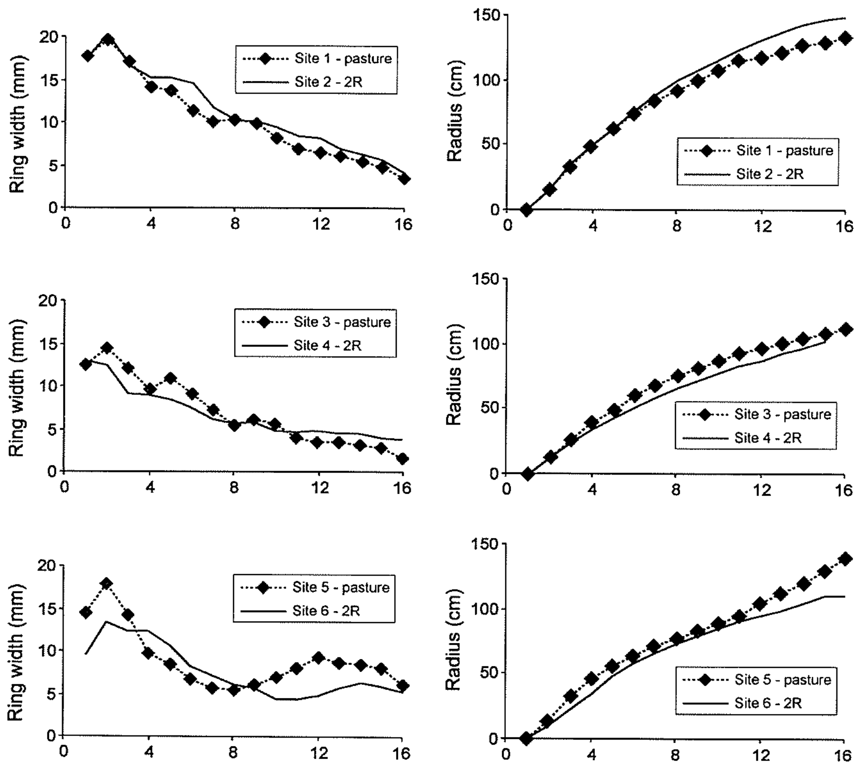


FIG. 2–Pairwise comparisons of pith-to-bark profiles for ring width (mm) and stem radius (cm).

first three rings, but then ring width decreased rapidly over the next few years before increasing again after Ring 8. The second-rotation site (Site 6) showed a steady decrease in ring width to Ring 12, followed by a slight increase. The increases in ring width for Sites 5 and 6 would appear to be thinning responses.

## Correlations between Traits

Correlations of tree size with average wood and fibre properties for each site (Table 3) were generally small, variable, and non-significant, indicating it was not possible to predict wood or fibre properties from tree diameter or height. The only significant correlations were between dbh and acoustic velocity, which were significantly negative at Sites 1, 2, and 4.

TABLE 3–Correlations of growth with wood and fibre properties for each site (N=10)

| Traits | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 |
|---|---|---|---|---|---|---|
| Dbh – fibre length | –0.01 | –0.27 | 0.38 | –0.34 | 0.15 | 0.33 |
| Dbh – fibre coarseness | 0.25 | –0.22 | 0.04 | –0.12 | 0.13 | –0.04 |
| Dbh – outerwood density | –0.11 | –0.31 | –0.15 | –0.30 | 0.15 | –0.22 |
| Dbh – microfibril angle | 0.55 | 0.37 | –0.01 | 0.60 | –0.10 | –0.44 |
| Dbh – acoustic velocity | –0.67* | –0.71* | 0.18 | –0.69* | –0.49 | –0.11 |
| Dbh – $MOE_{SS}$ | –0.59 | –0.60 | 0.15 | –0.47 | 0.00 | 0.25 |
| Height – fibre length | 0.42 | –0.24 | –0.25 | –0.16 | –0.04 | 0.17 |
| Height – fibre coarseness | –0.61 | 0.06 | –0.07 | 0.20 | –0.09 | 0.49 |
| Height – outerwood density | –0.03 | 0.45 | –0.01 | –0.13 | 0.02 | 0.23 |
| Height – microfibril angle | –0.38 | 0.23 | –0.04 | 0.48 | –0.20 | 0.26 |
| Height – acoustic velocity | 0.44 | 0.02 | 0.39 | –0.34 | –0.62 | 0.16 |
| Height – $MOE_{SS}$ | 0.50 | –0.07 | 0.29 | –0.36 | –0.22 | –0.07 |

* significant at $p<0.05$

Correlations amongst the wood and fibre properties for each site (Table 4) were also generally small, variable, and non-significant. The notable exception was the correlations for outerwood density and SilviScan average density. The lack of significant correlations between density and fibre coarseness was of interest as this indicates that density would not be a good predictor of coarseness.

## Pith-to-Bark Patterns of Change

Pith-to-bark changes in air-dry density (Fig. 3) indicated that, for the rings closest to the pith, there was little difference between the ex-pasture and second-rotation sites. However, beyond Ring 5 (approximately age 9, as the cores were taken at 1.3 m above ground) density increased rapidly for both site types, with the density of the second-rotation sites being consistently higher in the outer rings. Site 5

TABLE 4–Correlations between wood and fibre properties for each site (N=10).

| Traits | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 |
|---|---|---|---|---|---|---|
| Fibre length and fibre coarseness | 0.22 | 0.83** | 0.25 | 0.67* | 0.46 | –0.03 |
| Fibre length and pH | –0.41 | 0.43 | –0.39 | –0.18 | 0.03 | 0.20 |
| Fibre length and outerwood density | –0.09 | 0.27 | –0.21 | 0.03 | 0.27 | –0.11 |
| Fibre length and SilviScan density | –0.31 | 0.25 | –0.14 | 0.41 | 0.14 | 0.38 |
| Fibre length and microfibril angle | –0.54 | –0.30 | –0.28 | –0.73* | –0.44 | –0.73* |
| Fibre coarseness and pH | –0.43 | 0.60 | 0.12 | –0.22 | –0.41 | –0.03 |
| Fibre coarseness and outerwood density | –0.02 | 0.58 | 0.44 | –0.25 | 0.55 | 0.30 |
| Fibre coarseness and SilviScan density | –0.15 | 0.56 | 0.40 | 0.23 | 0.55 | 0.44 |
| Fibre coarseness and microfibril angle | 0.10 | –0.52 | –0.56 | –0.43 | 0.04 | –0.03 |
| pH and outerwood density | 0.06 | 0.44 | 0.43 | 0.42 | –0.38 | 0.19 |
| pH and SilviScan density | 0.70* | 0.41 | 0.23 | –0.14 | –0.41 | 0.40 |
| pH microfibril angle | 0.45 | –0.56 | 0.34 | 0.33 | –0.25 | –0.42 |
| Outerwood density and SilviScan density | 0.65* | 0.84** | 0.82** | 0.22 | 0.84** | 0.76** |
| Outerwood density and microfibril angle | –0.25 | –0.16 | –0.16 | 0.20 | 0.01 | 0.23 |
| SilviScan density and microfibril angle | 0.29 | –0.47 | –0.23 | –0.13 | 0.32 | –0.43 |

* significant at $p<0.05$
** significant at $p<0.01$

showed a change in the pattern of density from Ring 8 onwards, when density stopped increasing and levelled off. This information, combined with the change in ring width (Fig. 2) at the same ring, indicates that this site was thinned earlier than the compartment records indicate.

From the density graphs in Fig. 3 it would appear that the age of transition from juvenile to mature-type wood was the same for the two site types as the patterns of change from low to high density were very similar. When all of the ex-pasture or second-rotation sites were plotted together (Fig. 4), the patterns of change were very similar for each site class.

For microfibril angle, the shape of the pith to bark traces was very similar for the ex-pasture and second-rotation sites, indicating little effect of site type (Fig. 3). For Sites 1 and 2 the traces were almost identical, with the exception of the innermost ring. Similarly, for Sites 5 and 6 the traces were identical for the first 10 rings from the pith but the ex-pasture site (Site 5) had a higher microfibril angle in the outermost rings, possibly due to the early thinning. For the remaining pair of sites (Sites 3 and 4) the ex-pasture site had a higher microfibril angle from Rings 1 to 10 but identical microfibril angle from Ring 10 onwards. For this pair of sites, the microfibril angle for the ex-pasture site remained above the acceptable limit of 30° (as defined by Donaldson 1992) for around 3 years longer than the matched second-

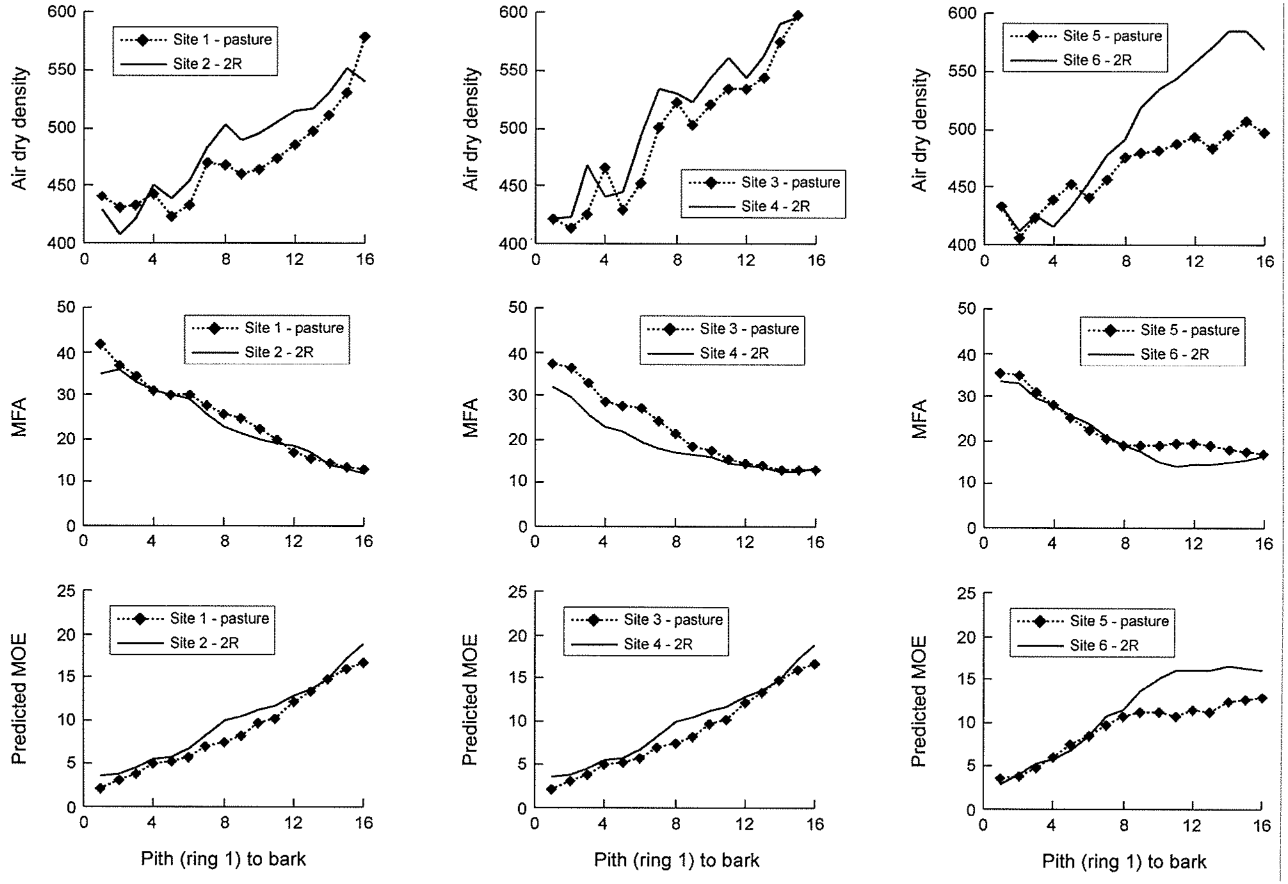


FIG. 3–Pairwise comparisons of pith-to-bark profiles for air-dry density (kg/m$^3$), microfibril angle (MFA in degrees), and predicted dynamic modulus of elasticity (MOE in GPa).

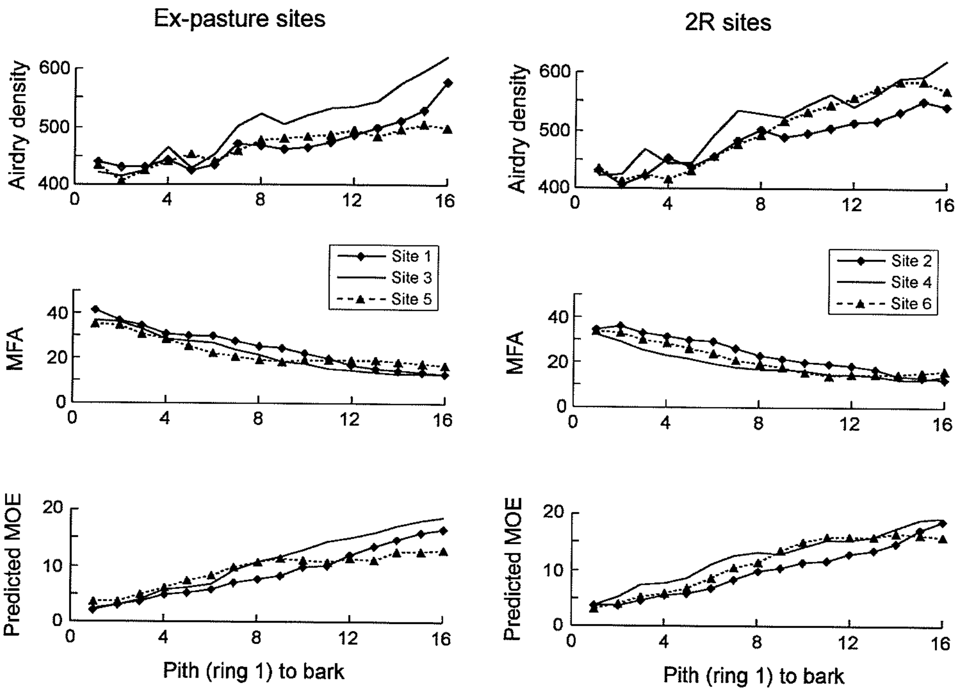


FIG. 4—Combined graphs for ex-pasture and second-rotation sites for air-dry density (kg/m$^3$), microfibril angle (MFA in degrees), and predicted dynamic modulus of elasticity ($MOE_{ss}$ in GPa).

rotation site. When the pairs of regression lines were tested to determine whether the lines for the pasture and second-rotation sites were parallel (Table 5), the only significant effect of site type found was for Sites 3 and 4, where there was a significant interaction between site type and ring number for microfibril angle. When all of the ex-pasture or second-rotation sites were plotted together (Fig. 4), the patterns of change were very similar with each site-class.

The patterns of change for air-dry density and microfibril angle are reflected in the $MOE_{ss}$ data (Fig. 3 and 4). Overall, there was little difference in the predicted $MOE_{ss}$ for Sites 1/2. The largest difference in $MOE_{ss}$ occurred for Sites 5/6 due to the differences between both density and microfibril angle in the outer rings. For both Sites 3/4 and 5/6, there was a significant interaction of ring number with site type for $MOE_{ss}$ (Table 5), indicating that the regression lines were not parallel.

## Value of the Acoustic Velocity Data

For the individual tree data, combined across sites, acoustic velocity in the butt log was a reasonable predictor of average microfibril angle ($R^2$ of 0.55) and $MOE_{ss}$ ($R^2$ of 0.63) (Table 6) but was less good at predicting fibre length ($R^2$ of 0.34) or

TABLE 5–Fitted regression equations for microfibril angle and $MOE_{ss}$ against growth ring from the pith for individual trees at breast height at each site. Each pair of sites was tested to determine whether the regression lines were parallel by fitting the interaction of site with ring number.

| Trait/site | Equation | $R^2$ (%) | Test for parallel regressions |
|---|---|---|---|
| Microfibril angle | | | |
| Site 1 | Y = 42.219–2.417*Ring+0.0343*Ring$^2$ | 98 | ns |
| Site 2 | Y = 38.629–1.957*Ring+0.0177*Ring$^2$ | 98 | |
| Site 3 | Y = 41.712–3.302*Ring+0.0915*Ring$^2$ | 99 | ** |
| Site 4 | Y = 34.263–3.003*Ring+0.1071*Ring$^2$ | 98 | |
| Site 5 | Y = 39.240–3.373*Ring+0.1305*Ring$^2$ | 96 | ns |
| Site 6 | Y = 39.132–3.570*Ring+0.1307*Ring$^2$ | 97 | |
| $MOE_{ss}$ | | | |
| Site 1 | Y = 2.039+0.485*Ring+0.0286*Ring$^2$ | 99 | ns |
| Site 2 | Y = 2.805+0.572*Ring+0.0243*Ring$^2$ | 99 | |
| Site 3 | Y = 0.449+1.300*Ring–0.0075*Ring$^2$ | 99 | ** |
| Site 4 | Y = 2.597+1.449*Ring–0.0268*Ring$^2$ | 98 | |
| Site 5 | Y = 1.667+1.382*Ring–0.0442*Ring$^2$ | 96 | ** |
| Site 6 | Y = –0.043+1.943*Ring–0.055*Ring$^2$ | 97 | |

* significant at p<0.05
** significant at p<0.01
ns not significant

TABLE 6–Fitted regression equations for acoustic velocity with a range of wood properties for both individual trees and site means.

| Trait/site | Equation | $R^2$ (%) |
|---|---|---|
| Individual trees | | |
| Fibre length | Y = 0.99 + 0.414 * velocity | 34 |
| Outerwood density | Y = 126.1 + 116.3 * velocity | 46 |
| Average microfibril angle | Y = 51.015 – 11.447 * velocity | 55 |
| Average $MOE_{ss}$ | Y = –10.204 + 8.0855 * velocity | 63 |
| Site means | | |
| Fibre length | Y = 0.6353 + 0.5458 * velocity | 84 |
| Outerwood density | Y = 24.714 + 153.82 * velocity | 86 |
| Average microfibril angle | Y = 55.474 – 13.092 * velocity | 92 |
| Average $MOE_{ss}$ | Y = –12.567 + 8.9633 * velocity | 82 |

outerwood density($R^2$ of 0.46). For site means, velocity was a good predictor for all traits, with the degree of variation explained ranging from 0.82 for average $MOE_{ss}$ to 0.92 for average microfibril angle.

## DISCUSSION

Overall, the wood and fibre properties produced on ex-pasture sites were consistently different to those from matched second-rotation sites. When results from the paired sites were examined, the ex-pasture sites produced wood with lower density, shorter fibres, lower fibre coarseness, higher pH, and higher average microfibril angle leading to a decrease in $MOE_{SS}$. However, the degree of variation between the sites was relatively large, with some ex-pasture sites producing better wood than second-rotation sites located in the same forest area with the same soil type and altitude. Thus, it is not possible to draw the conclusion that all ex-pasture sites are going to produce inferior-quality wood.

Differences in growth patterns were also found between the site types. However, examination of the pith-to-bark profiles for air-dry wood density indicated that the age of transition from juvenile to mature wood was the same for the two site types and was not affected by differing growth curves. These results agree with those of Cown (1992b) who found that growth rate, as reflected in ring width, had little if any effect on the corewood/maturewood transition.

Two issues are critical to determining the practical outcomes of these observed differences:

(1) Are there differences in the amount of juvenile corewood being produced?

(2) Does prior land-use, *per se*, alter the type of wood being produced in the inner and outer portions of the stem?

To assist with interpreting the results in relation to these issues, the data were combined to produce profiles of the wood quality for corewood and outerwood using Cown's (1992a) definition of the boundary between the two as the tenth growth ring. Results (Table 7) indicate that the ex-pasture sites produced 4–5% more corewood than their matched second-rotation sites for unthinned sites (sites 1 to 4). Results for Sites 5 and 6 are complicated by thinning operations being done at different ages, leading to differences in growth curves for the ex-pasture and second-rotation sites.

Prior land-use, *per se*, was also affecting the type of corewood being produced. Across all sites, the density of the corewood from ex-pasture sites was between 10 and 16 $kg/m^3$ lower than the second-rotation sites. The microfibril angle of the pasture corewood was also higher and, combined with the lower density, led to lower $MOE_{SS}$ for the corewood of the ex-pasture sites. For the unthinned sites, differences in mature wood density were similar in size to that for the corewood and there was little, if any, difference for microfibril angle or $MOE_{SS}$. For the thinned sites, there was a large difference in density for mature wood, and microfibril angle also differed in the outerwood.

TABLE 7–Summary of corewood and mature wood properties for each site.

| | Site | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Prior land-use* | Pasture | 2R | Pasture | 2R | Pasture | 2R |
| Thinned | No | No | No | No | Yes | Yes |
| Percentage final sectional area in inner 10 rings | 66 | 61 | 62 | 58 | 41 | 60 |
| Density ($kg/m^3$) | | | | | | |
| inner 10 rings | 446 | 457 | 466 | 482 | 449 | 459 |
| outerwood | 513 | 526 | 568 | 579 | 494 | 569 |
| Microfibril angle (°) | | | | | | |
| inner 10 rings | 30 | 28 | 27 | 22 | 25 | 25 |
| outerwood | 16 | 16 | 14 | 14 | 18 | 15 |
| $MOE_{ss}$ (GPa) | | | | | | |
| inner 10 rings | 6 | 7 | 7 | 10 | 8 | 8 |
| outerwood | 14 | 15 | 17 | 17 | 12 | 16 |

* 2R = second-rotation

However, these differences between the prior land-use classes are minimal when compared to the differences between the inner and mature wood for each site. For the unthinned sites, differences in density between corewood and mature wood ranged from 66 to 102 $kg/m^3$, and the microfibril angle was 8–15° lower for the mature wood. This resulted in the $MOE_{ss}$ for the corewood being approximately half of that found in the outerwood. Given these large differences within each tree, it would be expected that the greatest effect of prior land-use would be due to the increase in the volume of corewood rather than the changes in wood properties that can be ascribed to prior land-use *per se*.

The effects of these differences in corewood volume will depend upon which product is produced and the sensitivity of the process or product to changes in wood quality. For sawn timber, the increase in corewood volume is undesirable due to the lower density and stiffness of juvenile wood. However, Donaldson (1992) defined a microfibril angle of 30° as the cut-off point between acceptable and unacceptable wood quality based on modulus of elasticity and longitudinal shrinkage. Using this definition, the majority of the wood being produced would be of acceptable quality, with the exception of the first few rings adjacent to the pith.

For pulp, paper, and medium-density fibreboard manufacture both the process and the end-product are sensitive to differences between corewood and mature wood, but it is unclear what effect the changes in corewood volume would have. Paper made from corewood pulps has different properties to that made from outerwood. Corewood paper properties are associated with tracheids that have thin cell walls that flatten easily during beating, resulting in separation of fibre layers (Harris 1981). Papers made from corewood have high tensile and burst strength, and good conformability and printability (Walker & Nakada 1999). Similarly, for fibreboard Shupe *et al.* (1999) and Pugel *et al.* (1990a,b) found that corewood of *Pinus taeda* L. (loblolly pine) compacted to a greater degree during board manufacture. Despite differences in compaction ratio, little difference was found for modulus of rupture, modulus of elasticity, internal bond strength, water adsorption, or thickness swell between panels manufactured from either innerwood or outerwood. However, Pugel *et al.* (1990a,b) also pointed out that the higher compaction ratio meant that a greater volume of innerwood was required to produce a finished panel of a given desired density, with the additional volume of wood required being directly proportional to the density of the wood.

One important caution to note is that the results presented here are based on breast-height samples for most of the wood properties examined, with the exception of acoustic velocity, which was measured on a 5-m butt log. For most of the traits included, the patterns of within-tree variation have been examined for trees growing on forest sites and predictive relationships exist for extrapolating from breast-height to whole-tree values. However, the effect of prior land-use on within-tree variation is unknown. Thus, it is uncertain whether existing predictive relationships will be valid for use on different types of sites.

In conclusion, this study indicated that consistent differences in wood and fibre properties may be found between ex-pasture and second-rotation sites. However, due to variability within forest areas, some ex-pasture sites may produce better-quality wood than some second-rotation sites. Growth patterns also differed with prior land-use but it appeared that the age of change to mature-type wood was the same for the two site types. Overall, the major effect of site type would appear to come from an increase in the volume of juvenile corewood on the ex-pasture sites.

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