PATTERNS OF BASIC DENSITY VARIATION FOR *PINUS RADIATA* GROWN IN SOUTH-WEST SLOPES REGION OF NEW SOUTH WALES, AUSTRALIA

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ABSTRACT

Patterns of change from pith to bark and the distribution of variability in density across forest areas, sites, and trees were determined using data from breast-height cores taken from harvest-age *Pinus radiata* D. Don (ages 28 to 37 years) as part of a resource survey of four forest areas in the south-west slopes area of New South Wales. Seventeen of the sample sites had been thinned, one site was a thinning trial, and the other two sites were unthinned but matched to two of the thinned sites to determine the effects of thinning. Pith to bark cores were cut into five-ring segments and extracted basic density was determined for each segment.

Little difference in average basic density was found between the forest areas, particularly for the first 10 rings adjacent to the pith. The major source of variability was between trees within each site — this accounted for 77–92% of the total variation at each age. Thinning had no discernible significant effect on density at any age. Density in the outermost five-ring segment (corresponding to ages 23–28 to 32–37 years) was poorly predicted by juvenile core density (inner 10 rings), indicating little opportunity for forward or backward prediction of density.

Keywords: basic density; age trends; thinning; juvenile wood.

INTRODUCTION

When a large forest resource exists within a defined geographic area it is important to determine both the quality and the variability within that resource. For tree

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growth and form, ongoing inventory assessment is considered a routine forest operation that enables forward planning and management of future wood flow. Historically little attention has been paid to the wood quality of the resource, as conducting a resource survey for any wood property is a major undertaking. Within such a programme the number of regions to be sampled may be small but the intensity of sampling within the region will be controlled largely by the budget available. Such a sampling programme may need to continue over a number of years in order to accumulate a sufficiently large database, as was the case in New Zealand (Hughes & Mackney 1949; Loe & Mackney 1953; Harris 1965; Cown *et al*. 1991).

Basic density is a fundamental wood property that influences many end-product values including timber stiffness and strength, machinability, pulping characteristics, and paper quality (Cown & Kibblewhite 1980; Bamber & Burley 1983; Cown *et al.* 1991; Roper *et al*. 2004b). For *P. radiata*, density varies within each tree in a radial direction (Cown & McConchie 1980) with the centre of the tree containing a cylinder of lower-density juvenile corewood which is surrounded by annuli of increasingly dense wood as the tree ages (Cown 1980; Burdon *et al*. 2004). The difference between the density of the juvenile core of the tree and that of the outerwood can be quite large, and may in fact be larger than the difference between the outerwood density of adjacent trees within a stand. Patterns of change within a tree are important, as they will influence the processing properties of each log. Both the overall density and the shape of the density curve from pith to bark will also be affected by such factors as site, genotype, and silvicultural management of the stand.

The effect of site is complex and is confounded with differences in climate and soil type. In addition, applied silvicultural treatments may alter available soil moisture and nutrient status (Bamber & Burley 1983). Evidence that these factors will have an impact on wood density can be seen from studies on effects of drought, temperature, latitude, altitude, and soil type. The effect of drought varies depending upon which season the drought occurred in (Bamber & Burley 1983): a spring drought would decrease earlywood formation and increase density, whilst a summer and autumn drought would reduce density due to lack of latewood formation. A strong positive relationship between mature wood density and mean annual temperature has been found in New Zealand (Harris 1965). This temperature effect is related to both altitude and latitude — density decreasing with increasing latitude and altitude (Harris 1965; Cown *et al.* 1991; Cown 1992). In New Zealand rainfall has a small positive influence whilst soil fertility (ph, nitrogen, and phosphorus) has a negative effect on density (Cown *et al.* 1991; Cown 1992). In a broad-scale survey across NSW, Wilkes (1989) found a positive relationship between density and summer rainfall, and a negative relationship for density with winter rainfall and foliar phosphorus level, but no relationship with temperature. Soil type has a significant effect on wood basic density of *P. radiata* in the Gippsland region of Victoria according to Turvey & Smethurst (1985) but those authors found no effect for average rainfall.

Whether thinning has an identifiable effect on wood density appears to relate to the scale of assessment. When five-ring segments are used, little effect has been found (Cown 1973, 1974; Cown & McConchie 1981; Sutton & Harris 1974) due to the averaging effect of the segments (Raymond 2006). However, when density is determined on a finer scale, using X-ray densitometry, a decrease in density over a 4-year period was found by Cown (1974) and Nyakuengama *et al*. (2002) although Sutton & Harris (1974) found no such decrease in average density.

Forests NSW has undertaken a wood density survey within one of its major growing region, the south-west slopes area, which is centred on the town of Tumut in southern NSW. This study aimed to determine how pith-to-bark density varied within different areas of the region. In particular it addressed the following questions:

- Are there differences between forest areas?
- Which forest areas produce the highest density wood?
- Is the pattern of change from pith to bark consistent across forest areas?
- How is the variability distributed between forest areas, sites within forests, and trees within sites?
- What effect does thinning have?
- Can density at a young age be used to predict density at final harvest? Conversely, is outerwood density at harvest a reliable predictor of density in the juvenile core?

MATERIALS AND METHODS

The four forests sampled in this study are located around the town of Tumut (35°30´S, 148°22´E, 280 m a.s.l.): Buccleuch to the north-east, Bago to the south, Green Hills to the south-west, and Carabost to the south-west of Green Hills (Fig. 1). Three of these forests (Buccleuch, Bago, and Green Hills) are at similar altitude, on similar geology (Table 2), and experience similar climatic conditions (Table 1). Carabost is approximately 300 m lower in elevation, with higher average temperatures, lower rainfall, and different geology (Tables 1 and 2).

As a significant area of this resource is approaching harvest age (around 30 years), the survey aimed to quantify both the mean and the variation for wood density within each of the forest areas. Sample sites (Table 2) were selected to cover the range in site quality within each forest area. All sample sites were in mature stands approaching clearfelling and most of the sites had been thinned during their life (*see*

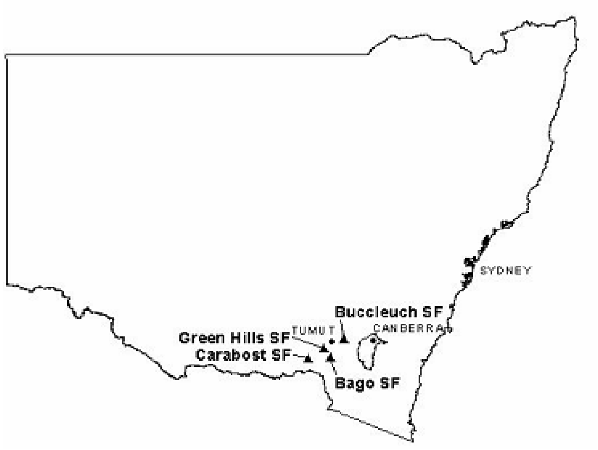

FIG. 1–Geographic location of the forest areas assessed

TABLE 1–Average climatic data for each forest area.

	Bago	Buccleuch	Carabost	Green Hills
Altitude (m a.s.l.)	920	870	560	815
Annual mean temperature (°C)	10.5	11.0	12.2	10.9
Maximum summer temperature (°C)	25.1	26.1	28.3	26.1
Minimum winter temperature (°C)	–0.1	–0.1	0.2	–0.1
Annual precipitation (mm)	1270	1270	940	1220

Table 2 for details). To determine the effects of thinning, a thinning trial was also sampled (Site 12 in Buccleuch) and two pairs of matched sites (thinned and unthinned) were sampled in 2005 (sites 100 and 101 in Buccleuch and 104 and 105 in Green Hills). For the matched pairs of sites, 20 trees were sampled from both thinned and unthinned sections of the same compartment or adjacent compartments.

For *P. radiata*, breast-height wood density has been found to be a good predictor of average stem density (Wilkes 1989; Kininmonth & Whitehouse 1991; Roper *et al.* 2004a) so this study was based on breast-height samples only. Pith-to-bark cores were collected at two different times: the first batch in 2000 and the second in 2005. For the first batch, cores were collected from 30 trees at each of 11 sites and from 40 trees at a twelfth site, the thinning trial. In 2005 cores were collected from 20 trees at an additional eight sites. A single 5-mm core was collected from each tree, labelled, and stored inside a drinking straw. Each core was dissected into five-ring segments commencing from the bark. Each segment was resin-extracted and basic density was determined using the maximum moisture method (Smith 1954). Due to the rapid initial increase in density from the juvenile centre of the tree outwards, all data were collated from the pith end of the core prior to analysis. Data from all sites except the thinning trial were then collated into a single file for analysis.

TABLE 2–Details for each of the sampling sites

Site No.	Planted	Age (years)	Forest	PRC*	Silviculture
2000 sampling					
1	1970	30	Bago	9	Thinned
25	1970	30	Bago	11	Thinned
5	1970	30	Buccleuch	11	Thinned
12	1972	28	Buccleuch	9	Thinning trial
26	1964	36	Buccleuch	11	Thinned
31	1965	35	Buccleuch	11	Thinned
20	1970	30	Buccleuch	9	Thinned
22	1970	30	Buccleuch	11	Thinned
4	1970	30	Carabost	5	Thinned
23	1970	30	Carabost	5	Thinned
24	1965	35	Carabost	5	Thinned
19	1970	30	Green Hills	9	Thinned
2005 sampling					
103	1969	36	Bago	9	Thinned
100	1969	36	Buccleuch	11	Thinned
101	1969	36	Buccleuch	11	Unthinned
106	1970	35	Buccleuch	11	Thinned
107	1969	36	Carabost	5	Thinned
102	1968	37	Green Hills	11	Thinned
104	1972	33	Green Hills	9	Thinned
105	1972	33	Green Hills	9	Unthinned

* Parent Rock code from Turner *et al*. (1996)
Code 5 is argillaceous group including slates, shales, mudstones, greywacke
Code 9 is feldspathic-micaceous group including grandiorite
Code 11 is ferro-magnesian group including basalt, dolerite, gabbro

Site averages were plotted for each forest area to determine patterns of change. The distribution of variation within the data was determined using analyses of variance for each segment of the cores. The initial model contained terms for forest, and site within forest, and aimed to determine whether there were greater differences between forest areas than between sites within each area, or between trees within sites. The results of this analysis were used to determine the distribution of the variance components for each five-ring segment. The same sort of analysis of variance was then applied to each forest area to determine whether sites within the forests differed more than trees within the sites. No attempt was made to relate the observed density variation to site or climatic variables because of the small number of sample sites, their relatively small geographic spread, and the lack of major variation in the climatic variables across these areas.

The effect of thinning was determined by analysis of variance of the data for each segment for the thinning trial and for both of the matched pairs of sites. The samples taken from the thinning trial consisted of 10 cores from each of four treatments:

(1) Age 15 first thin to 11 m^2/ha followed by second thin at age 23 to 16 m^2/ha

(2) Age 15 first thin to 21 m^2/ha followed by second thin at age 23 to 22 m^2/ha

(3) Age 15 first thin as third outrow to 21 m^2/ha followed by second thin at age 23 to 22 m^2/ha

(4) Control.

To determine the feasibility of either forward or backward prediction of density, the correlations between the outerwood density (outer five rings) and that of the inner segments were determined. The juvenile core of the tree was defined as the inner two segments of the core (following Cown & Kibblewhite 1980) and the average density of these segments was used to define juvenile density. The density of the third inner-most segment (laid down around the transition from juvenile to more mature-type wood) was also included in the analysis to determine whether this was a better predictor of final density than the juvenile density. Correlations between outerwood density and both juvenile and third-segment density were determined for all sites.

RESULTS AND DISCUSSION

Distribution of Variation

The average densities (Fig. 2) were slightly higher than those found by Wilkes (1989) across NSW — 348 to 355 kg/m^3 for the innermost segment *vs* Wilkes

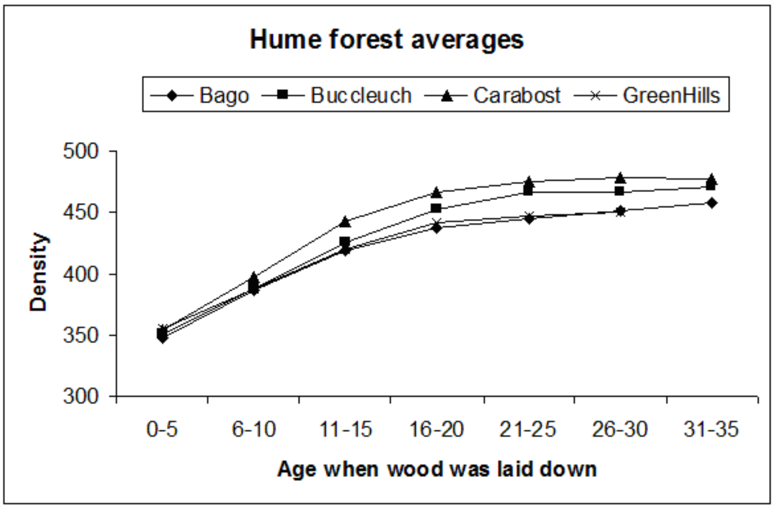

FIG. 2–Plots of average density for each segment from each forest area.

310 kg/m^3, and 458 to 477 kg/m^3 for the outerwood segment *vs* Wilkes 466 kg/m^3. The outerwood densities are very similar to those found in the Mt Gambier area of South Australia (Roper *et al*, 2004a). According to the New Zealand ranking system of Cown *et al.* (1991), based on outerwood density, these sites would fall into the medium density class.

Carabost had the highest average density from pith to bark (Fig. 2), followed by Buccleuch, with Green Hills and Bago having almost identical average densities. However, the differences between the forests were not large, particularly within the juvenile core of the trees (inner two segments) where there was remarkably little difference between the averages for the forest areas (Fig. 2). This is reflected in the results for analyses of variance, where no significant effect was found for forest in the innermost segments (Table 3). Similarly for these segments, the proportion of variance attributable to forest was zero (Table 4). As the trees aged, the difference between forest areas increased and became significant (Table 3) but overall it did not contribute a large proportion of the variance, increasing to a maximum of 13% around age 25 (Table 4). At all ages, the majority of the variation in density occurred between trees within sites (Table 3), ranging from 77% at age 25 up to 92% of the total variation at age 5.

Similar results have been reported by Wilkes (1989) and Cown *et al.* (1991). In the broad-scale survey across NSW, Wilkes found that site effects accounted for a small proportion of the total variation and that variability between trees within a site increased with age. In New Zealand, Cown *et al.* (1991) found very little difference between regions across New Zealand for the innermost five-ring segment (range of 340 to 355 kg/m^3). Regional differences became more pronounced with age to reach a range of 439 to 514 kg/m^3 at ages 31 to 35. Cown *et al.* (1991) also reported substantial variation between sites within regions.

The separation of the forest areas with age is reflected in the ratio of the density of the pith segment to the outermost segment, which varied from 74% for Carabost and Buccleuch to 76% for Bago and 79% for Green Hills. For the juvenile core (average of the inner two segments) the ratio of density with the outermost segment ranged from 78% for Buccleuch to 82% for Green Hills. So, on average the density in the centre of the trees was around 20% lower than that at the bark.

Sites within forest areas generally showed little difference, contributing a maximum of 14% of the total variance (Table 4). For Bago and Carabost there was no significant difference between sites at any age (Table 3, Fig. 3). For Buccleuch there were significant site effects at each age but the spread of sites was not large (Fig. 3). Green Hills showed an interesting result with significant differences between sites apparent at all ages (Table 3). However, examination of the averages for each site (Fig. 3) indicated that one site (102) was very different. This site was on a different

TABLE 3–Analyses of variance for all data combined and for each forest area. Values presented are mean squares for each level of the analyses. DF is the degrees of freedom.

	DF	Age when segment was laid down (years)					
		0–5	6–10	11–15	16–20	21–25	26–30
All data combined							
Forest	3	1614	4347	12711 *	14093 *	22521 *	15729 *
Site within forest	15	2891 **	5483 **	3270 **	3558 **	4244 **	3563 **
Residual	467	844	1073	961	988	989	1065
Bago							
Site	2	159	674	653	911	271	582
Residual	77	960	1246	910	965	985	804
Buccleuch							
Site	7	2711 **	5142 **	3887 **	5555 **	6674 **	4572 **
Residual	201	754	1011	1016	1075	974	1080
Carabost							
Site	3	2088	2566	104	1550	479	1262
Residual	104	1118	1307	1054	982	967	1065
Green Hills							
Site	3	5935 **	12399 **	6740 **	2669 *	4989 **	5466 **
Residual	85	617	777	763	810	1056	1249
Green Hills minus site 102							
Site	2	2605 *	363	84	916	1768	4369 *
Residual	66	585	754	769	819	1040	1271

** p<0.01, * p<0.05

TABLE 4–Distribution of variation for all data combined.

	Age when segment laid down (years)					
	0–5	6–10	11–15	16–20	21–25	26–30
Variance components						
Forest	0	0	88	89	164	104
Site within forest	74	173	95	108	132	95
Residual	844	1073	961	988	989	1065
Percentages						
Forest	0	0	8	8	13	8
Site within forest	8	14	8	9	10	8
Residual	92	86	84	83	77	84

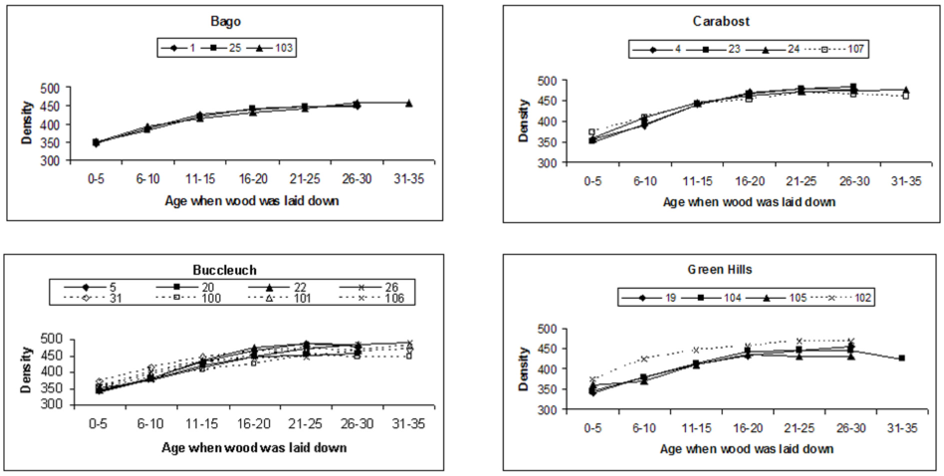

FIG. 3–Plots of averages for each site within each forest area.

parent rock code to the other sites. When the analysis was rerun excluding this site, there was very little difference between the remaining sites (Table 3).

The lack of differences between forest areas and sites in this study was not unexpected given the relatively uniform climate and soil types within this region. The only forest area which differed in climate and soil type was Carabost which was at lower altitude, with higher average temperatures, lower rainfall, and different geology. These factors would appear to be responsible for Carabost having the highest reported densities.

Effect of Thinning

Thinning was found to have very little effect on wood density either in the thinning trial or in the two pairs of sites. No significant difference between treatments was found for any segment in the thinning trial (Table 5), indicating there was more

TABLE 5–Results of analyses of variance for thinning effects. Values presented are mean squares for each level of the analyses. DF is the degrees of freedom.

	DF	Age when segment was laid down (years)					
		0–5	6–10	11–15	16–20	21–25	26–30
Thinning Trial Site 12							
Treatment	3	582	86	1157	2299	849	
Residual	36	821	1188	1371	1970	1535	
Buccleuch paired sites							
Treatment	1	0.3	1928	2901	8428 **	2462 *	3478 *
Residual	38	914	1514	1033	708	591	766
Green Hills paired sites							
Treatment	1	2624 *	475	136	736	2569	2482
Residual	37	479	574	881	749	787	935

** p<0.01, * p<0.05

variation within each treatment than between treatments. So, even though the unthinned treatment had the highest density in the outer segments (Fig. 4), this difference was not significant. For the paired sites in Buccleuch there was a significant difference after age 20, which would correspond to wood laid down after first thinning at age 19. For the Green Hills plots the only significant difference was for the innermost segment (Table 5) which was laid down long before any thinning treatment was applied. At all other ages the thinned trees actually had a higher density than the unthinned trees (Fig. 4) but this difference was not statistically significant.

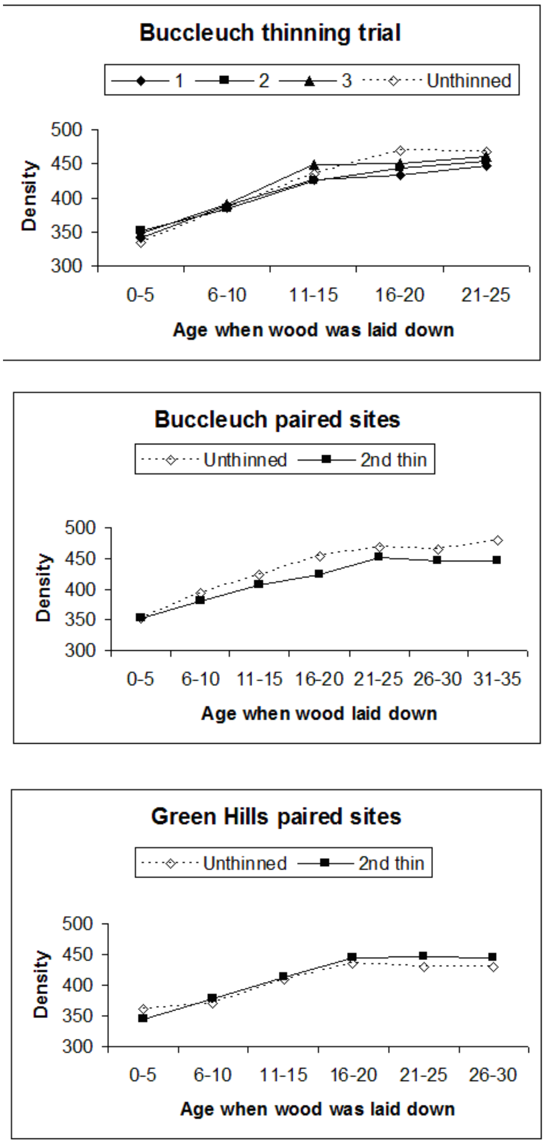

FIG. 4–Plots of pith to bark density for thinning treatments. For the Buccleuch thinning trial the treatments are described under Materials and Methods.

The lack of a significant effect of thinning agrees with the results of Cown (1973, 1974) and Sutton & Harris (1974) who also found no significant effect when examining density using five-ring segments. The absence of a discernible effect may be due to the sampling strategy used, with the averaging effect of the five-ring segments hiding any response (Raymond in press). When density was determined on a finer scale using X-ray densitometry, a small decrease after thinning was found by Cown (1974) and Nyakuengama *et al.* (2002). However, density recovered to the previous level within 4 years.

Potential for Forward or Backward Prediction of Density

The feasibility of either forward or backward prediction of density was determined using the correlations between the outerwood density (outer segment) and the juvenile density (inner 10 rings) and density of the third segment from the pith. Outerwood density was a poor predictor of juvenile core density, with only nine out of 19 correlations being significant (Table 6) and most correlations being relatively low (Fig. 5). This indicates that the outerwood density at harvest age will not

TABLE 6–Correlations between density of outer five rings with density of juvenile corewood (average of inner two segments laid down before approximately age 10) and with density of the third segment laid down before age 15.

Site No.	Forest	Outer–juvenile	Outer–third segment
2000 sampling			
1	Bago	0.509 **	0.661 **
25	Bago	0.327 *	0.511 **
5	Buccleuch	0.286	0.774 **
20	Buccleuch	0.176	0.489 **
22	Buccleuch	0.394 *	0.564 **
26	Buccleuch	0.509 **	0.491 **
31	Buccleuch	0.195	0.574 **
4	Carabost	0.660 **	0.749 **
23	Carabost	0.278	0.538 **
24	Carabost	0.278	0.509 **
19	Green Hills	0.269	0.652 **
2005 sampling			
103	Bago	0.058	0.680 **
100	Buccleuch	0.380	0.456 *
101	Buccleuch	0.213	0.450 *
106	Buccleuch	0.313	0.569 **
107	Carabost	0.465 *	0.855 **
102	Green Hills	0.556 *	0.411
104	Green Hills	0.647 **	0.760 **
105	Green Hills	0.645 **	0.727 **

** $p<0.01$, * $p<0.05$

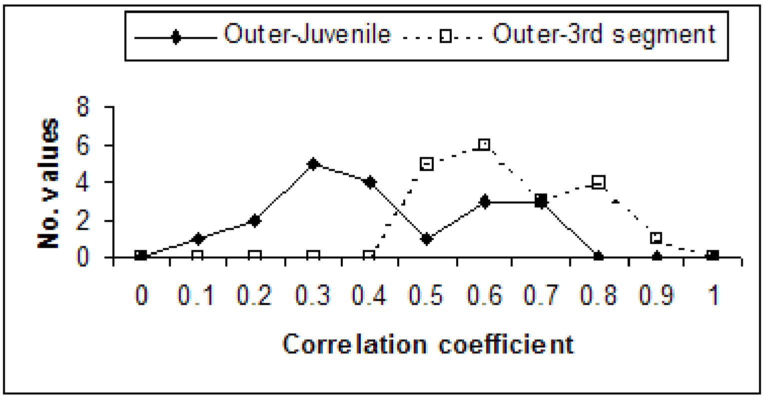

FIG. 5–Distribution of coefficients for the within-site correlations of outerwood density with juvenile or third segment density.

provide a good indication of the density of the juvenile core of the tree. Conversely, it would not be possible to use the juvenile density to predict the final harvest-age density of the outerwood.

A similar poor relationship between innerwood and outerwood was found by Wilkes (1989) who noted a significant interaction between site and wood zone, and that sites were ranked in a different order for innerwood and outerwood density. In New Zealand, Cown *et al.* (1991) found the mean corewood density (rings 1–10) could explain around 50% of the variation in outerwood density (rings 21–25). This was attributed to the greater variation in the outerwood density due to the larger and cumulative effect of environmental influences. They concluded that early density assessment was not a useful predictor of mature wood density as the 95% confidence interval on the predictions would be ±50 kg/m^3.

However, the current study suggests that the density of the third segment out from the pith may be a much better predictor of the final outerwood density, with correlations ranging from 0.41 to 0.77, and 18 out of 19 correlations being significant (Table 6, Fig. 5). This third segment is being laid down after age 10, when the trees are expected to have passed through the transition from juvenile to more mature-type wood. For forward projection of final harvest density it appears that it is necessary to wait at least 15 years to gain reliable predictions. This may be why Cown *et al.* (1991) recommended sampling trees older than age 15.

CONCLUSIONS AND PRACTICAL IMPLICATIONS

Average densities within the region were within the moderate range as defined in New Zealand, with outerwood densities similar to those found in the Mt Gambier area of South Australia. Little difference was found between the different forest areas for basic density at any age, indicating there is no need to stratify the region on the basis of density. The majority of the variation occurred between trees within each site. In terms of the practical implications for managing wood flow, this study presents no evidence indicating a need to segregate out specific areas of high- or low-density wood.

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