VARIATION IN WHOLE-TREE BASIC WOOD DENSITY FOR A RANGE OF PLANTATION SPECIES GROWN IN NEW ZEALAND

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ABSTRACT

Whole-tree basic wood density of individual trees of a variety of species has been determined in many different studies in New Zealand since 1977. These data were recently collated, and whole-tree values for each species have been aggregated across sites into 5-year age-classes, from <7 years up to 70 years. Means, ranges, and standard deviations of each species/age-class have been tabulated for a total of 968 trees and 13 species or species groups, with numbers of trees/species varying from 15 to 232. Sites sampled were mainly in the central and northern parts of the North Island (latitude 39°30′–35°25′S). Logarithmic regression equations fitted to the age-class mean densities for each species have provided predictions of whole-tree basic density with age and, in conjunction with predicted volume yields, were used in a related study to predict stem dry matter production per hectare for different species.

The species included were: *Acacia dealbata* Link., *A. mearnsii* De Wild., cypresses (data from *Chamaecyparis lawsoniana* (Murray) Parl., *Ch. nootkatensis* (D.Don) Spach × *Cupressus macrocarpa*, *C. lusitanica* Miller, and *C. macrocarpa* Gordon were amalgamated), *Pseudotsuga menziesii* (Mirbel.) Franco, *Eucalyptus fastigata* Deane et Maiden, *E. globoidea* Blakely, *E. globulus* Labill., *E. maidenii* Labill., *E. muelleriana* Howitt, *E. nitens* (Deane et Maiden) Maiden, *E. pilularis* Smith, *E. regnans* F.Mueller, and *E. saligna* Smith.

Predicted mean whole-tree basic density (from logarithmic regression) for the eucalypts (30-year-old trees) varied from 452 kg/m^3 *for E. regnans* to 623 kg/m^3 for *E. globoidea*. No data at age 30 years were available for *Acacia mearnsii* and *E. maidenii* but their mean density was respectively 658 kg/m^3 at age 14 and 572 kg/m^3 at age 11 years. Whole-tree mean density was about 418 kg/m^3 for the cypresses and 406 kg/m^3 for *Ps. menziesii*, almost irrespective of tree age.

A notable feature of these data was the great variability in density between trees in a stand, but variation in whole-tree density with age showed consistent patterns for different species, in spite of confounded effects of site and stocking.

Keywords: wood density; density/age regression; *Eucalyptus fastigata*; *Eucalyptus globoidea*; *Eucalyptus globulus*; *Eucalyptus maidenii*; *Eucalyptus muelleriana*; *Eucalyptus nitens*; *Eucalyptus pilularis*; *Eucalyptus regnans*; *Acacia dealbata*; *Acacia mearnsii*; *Cupressus macrocarpa*; *Cupressus*

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lusitanica; Chamaecyparis lawsoniana; Chamaecyparis nootkatensis × *Cupressus macrocarpa; Pseudotsuga menziesii.*

INTRODUCTION

Volume growth rate varies widely amongst species that are being grown commercially for solid wood and reconstituted products, or are being evaluated for these purposes as possible alternatives to *Pinus radiata* D.Don in New Zealand. Relatively fast growth is a prerequisite for consideration as a candidate species. Basic wood density is another important element of productivity, particularly in the production of pulp and reconstituted wood products, and it is also an important driver of end-product quality, both for solid wood and for pulp (Kibblewhite 1999; Kibblewhite & Shelbourne 1997; Cown 1999).

It was expected that there might be substantial differences between species in their stem dry matter production per hectare per year (based on volume growth and wood density) and thus in the amount of carbon that they could sequester. As part of a public-funded research programme on carbon sequestration, a study was initiated to compare the stem dry matter production of several plantation forest species grown in New Zealand. This entailed combining existing growth, yield, and wood-density information to predict dry stemwood production per hectare at different ages and at two different stockings. In our study, information on whole-tree basic wood density, collected over the last 23 years, was collated for 16 plantation forest species for which appropriate density data were available. The growth, yield, and stem dry-matter information, which utilise the results of this study, have been reported by Berrill *et al.* (in prep.).

METHODS

Collation of Whole-tree Basic Wood Density by Species and Age-class

Wood density has been measured for several different species at different ages, grown throughout New Zealand, though stands sampled for a large proportion of the studies were situated in the northern half of the North Island. The investigation reported here involved collating all available whole-tree wood density data for 16 species (Frederick *et al.* 1982; Jansen 1998; Kibblewhite *et al.* 2000; Lausberg *et al.* 1995), regarded as alternatives to *P. radiata*. Cross-sectional discs from different sample heights had been used in all studies to estimate weighted whole-tree basic density (as described below).

Data from forest tree species that appeared well adapted in the North Island, with commercial potential, and of which a sufficient number of trees had been sampled, were included in this study. The species were: *Acacia dealbata*, *A. mearnsii*, *Chamaecyparis lawsoniana*, *Ch. nootkatensis* × *Cupressus macrocarpa*, *C. lusitanica*, *C. macrocarpa*, *Pseudotsuga menziesii*, *Eucalyptus fastigata*, *E. globoidea*, *E. globulus*, *E. maidenii*, *E. muelleriana*, *E. nitens*, *E. pilularis*, *E. regnans*, and *E. saligna*. Data from the four cypresses (*Cupressus* and *Chamaecyparis* spp.) were amalgamated because insufficient trees had been sampled per species. This sampling and subsequent collation did not take site, genetic, or silvicultural factors into account, mainly because there were insufficient trees sampled in each species for the data to be broken down further. Inspection of the data also gave some confidence that site and stocking effects on wood density of a species were much less important than phenotypic variation amongst individual trees within sites.

More recent studies have sampled trees both by increment cores at breast height and by a full set of discs up the stem, which enabled regression relationships to be established between outerwood core density and whole-tree density for each species. This allows whole-tree density to be predicted using non-destructive increment-core sampling.

Relationship of individual whole-tree density data to age was quantified by regression analysis for each species. Linear ($y = a + bx$) and logarithmic equations ($y = a + b \ln x$) were tested. The equation that gave the highest R^2 value was selected for each species.

Density Determination Procedures

For calculating whole-tree weighted basic density, felled trees were cross-cut to provide 50-mm cross-sectional discs, sampled up the stem, usually at 0.15 m, 1.4 m, 5 m, and then at regular 5-m intervals down to a small-end diameter of approximately 100 mm. Disc diameters inside bark were recorded.

In the laboratory, disc densities were measured on the whole disc or on pith-to-bark sectors. The pith-to-bark sectors were usually sectioned into 5-ring blocks but if ring counting was difficult, sampling could be at regular intervals, radially, of about 60 mm.

Basic density of each disc was derived from volume, estimated by water displacement, and oven-dry weight. Densities of discs at either end of each log (stem section between disc samples) were then weighted by mean disc area, to give density of each "log", and were then weighted by log volume to give weighted whole-tree mean density.

RESULTS AND DISCUSSION

Since 1977, 100 separate studies have been carried out at the New Zealand Forest Research Institute involving as many stands and 15 species. Numbers of trees sampled per stand varied widely from 1 to 66, with 21 studies of 1–4 trees each, 55 studies with 5–10 trees, 16 studies of 11–20 trees, and eight studies with more than 21 trees. Location of the stands was predominantly in the central North Island, with 65 stands (latitude 39°30′–37°30′S). There were 19 stands from Auckland northwards and in the Coromandel peninsula (<37°30′S), seven on the East Coast (38°–39°35′S), and the other seven stands were in various parts of the South Island. Elevations were predominantly from sea level to 600 m.

Average whole-tree basic density of successive 5-year age-classes was calculated for each species from the unweighted individual tree values from 100 stands and 968 trees in all (Table 1). Standard deviations, number of trees and number of stands in which these occurred, and their average age are shown for each species age-class.

Species Regressions of Whole-tree Density on Age-class

For all species excluding the cypress group (where the density age trend was relatively flat) the logarithmic equation was superior to the respective linear equation in terms of R^2.

Logarithmic regressions of density on age are shown for each species in Fig. 1, which includes the equations which provided the best fit to the data and R^2 values, and these were used to predict age-class mean values (Table 1). A comparison of regression lines for all species is given in Fig. 2. Of the 13 species and species groups, seven had adequate data for

TABLE 1–Whole-tree basic density (kg/m³) by 5-year age-classes across sites for 13 species/species groups

Species	Age (years)						S. e.*
	<7	8–12	13–17	18–22	23–27	≥30	
A. dealbata							
Mean	334	477	468			631	67.1
S.d. (No.trees)	37 (15)	59 (2)	113 (6)			85 (5)	
Avg. age (†)	4 (1)	12 (1)	14 (2)			40 (1)	
Pred. mean	*360*	*447*	*498*	*534*	*563*	*585*	
A. mearnsii							
Mean	473		658				40.0
S.d. (No.trees)	51 (10)		19 (11)				
Avg. age (†)	3 (2)		14 (1)				
Pred. mean	*541*	*616*	*661*	*692*			
Cypresses							
Mean			431		396	404	32.4
S.d. (No.trees)			36 (7)		19 (5)	37 (107)	
Avg. age (†)			13 (1)		24 (5)	42 (11)	
Pred. mean			*420*	*420*	*420*	*420*	
Ps. menziesii							
Mean					415	414	27.7
S.d. (No.trees)					26 (45)	30 (187)	
Avg. age (†)					27 (2)	44 (8)	
Pred. mean				*394*	*401*	*406*	
E. fastigata							
Mean	385	413	474	499	475	501	31.7
S.d. (No.trees)	20 (5)	23 (5)	33 (132)	35 (4)	18 (9)	16 (5)	
Avg. age (†)	2 (1)	7 (1)	17 (6)	19 (1)	23 (1)	43 (1)	
Pred. mean	*420*	*450*	*468*	*480*	*490*	*498*	
E. globoidea							
Mean			588			646	35.4
S.d. (No.trees)			26 (5)			36 (13)	
Avg. age (†)			15 (1)			43 (3)	
Pred. mean		*527*	*563*	*588*	*607*	*623*	
E. globulus							
Mean	480	502					39.9
S.d. (No.trees)	27 (5)	46 (25)					
Avg. age (†)	7 (1)	10 (3)					
Pred. mean	*434*	*507*	*550*				
E. maidenii							
Mean	550	571					33.5
S.d. (No.trees)	24 (5)	35 (25)					
Avg. age (†)	7 (1)	10 (3)					
Pred. mean	*543*	*571*	*587*				
E. muelleriana							
Mean			536			551	27.2
S.d. (No.trees)			18 (10)			17 (5)	
Avg. age (†)			15 (1)			45 (1)	
Pred. mean		*504*	*521*	*532*	*541*	*548*	

* √ Regression mean square error

† No. of stands in parentheses

TABLE 1–cont.

Species	<7	8–12	13–17	18–22	23–27	≥30	S. e.*
	Age (years)						
E. nitens							
Mean	414	439	477			548	32.5
S.d. (No.trees)	34 (5)	28 (45)	35 (44)			29 (7)	
Avg. age (†)	2 (1)	9 (6)	15 (2)			30 (1)	
Pred. mean	*411*	*453*	*477*	*495*	*508*	*519*	
E. pilularis							
Mean			563				46.1
S.d. (No.trees)			46 (20)				
Avg. age (†)				15 (1)			
Pred. mean			*497*	*563*	*610*		
E. regnans							
Mean	382	391	414	444	459	489	33.2
S.d. (No.trees)	30 (14)	31 (48)	32 (28)	37 (41)	1 (2)	39 (8)	
Avg. age (†)	3 (2)	8 (7)	15 (4)	21 (4)	27 (2)	65 (3)	
Pred. mean	*379*	*407*	*424*	*436*	*445*	*452*	
E. saligna							
Mean	431	420			565	672	52.9
S.d. (No.trees)	28 (15)	31 (15)			35 (16)	50 (7)	
Avg. age (†)	3 (2)	7 (2)			25	44	
Pred. mean	*447*	*501*	*533*	*555*	*573*	*587*	

* √ Regression mean square error

† No. of stands in parentheses

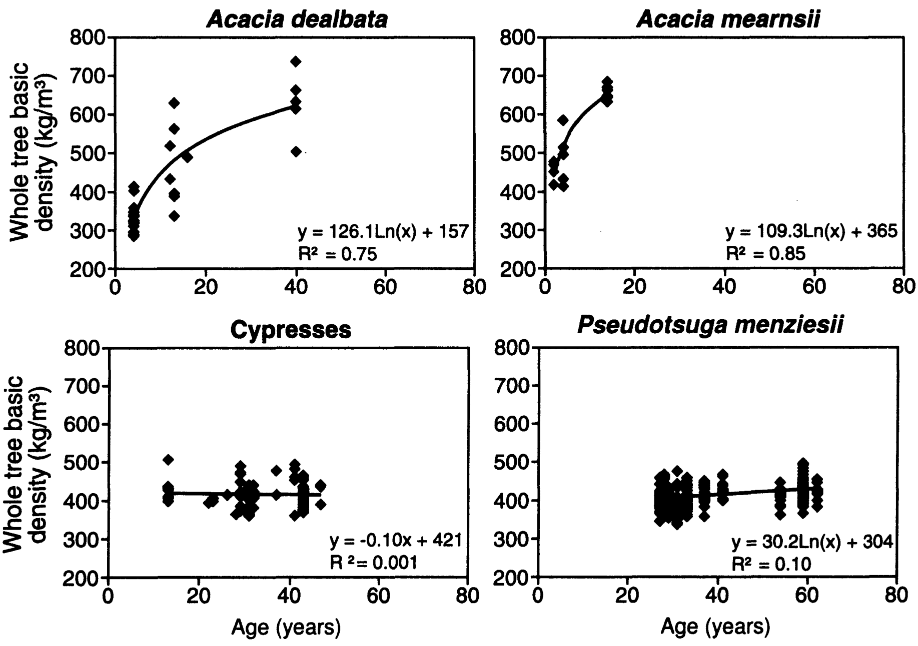

FIG. 1–Whole-tree basic density regressions (kg/m^3) on age.

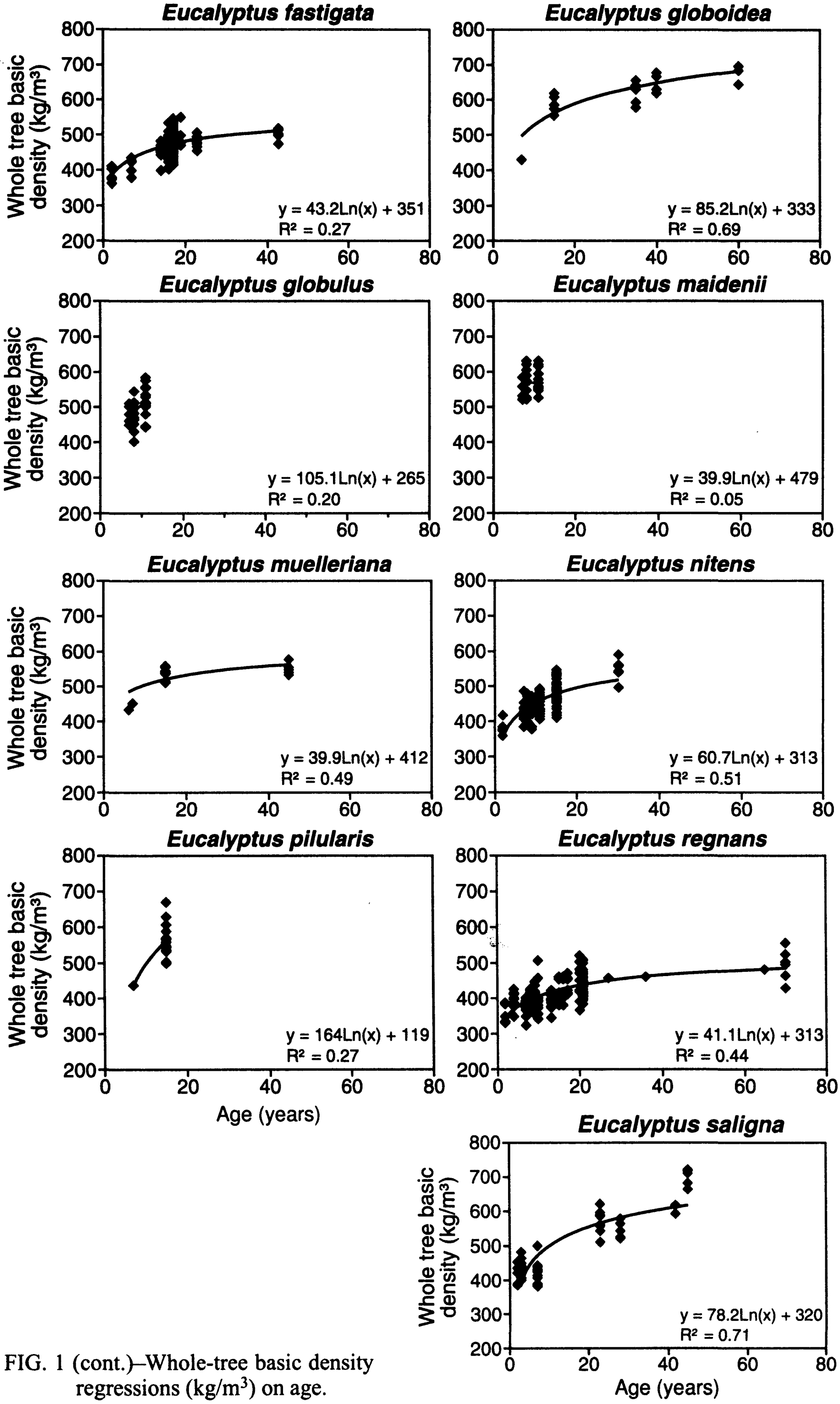

FIG. 1 (cont.)–Whole-tree basic density regressions (kg/m^3) on age.

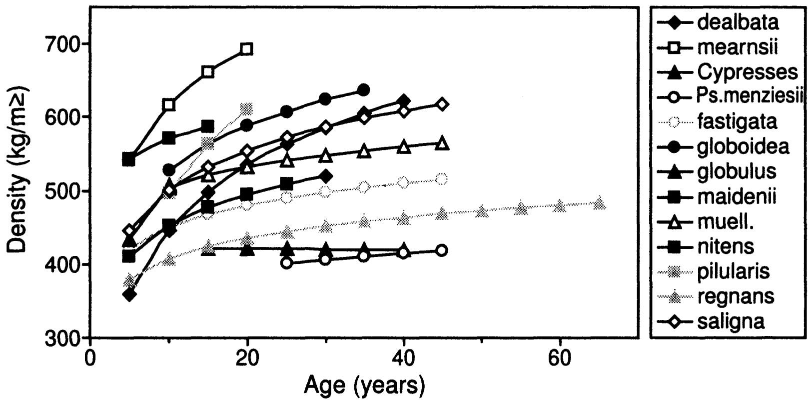

FIG. 2–Comparison of regressions of whole-tree basic density on age for 13 species and species groups.

estimating the regressions. These were *E. fastigata, E. nitens, E. regnans, E. saligna, A. dealbata, Ps. menziesii*, and the cypresses. The other species were represented in only one or two 5-year age-classes, making any estimation of the age-density relationship very tenuous.

Acacia dealbata

A total of 28 trees in five studies for this species ranged in age from 4 to 40 years. Most of the trees were from the central North Island. Of all 16 species, *A. dealbata* showed the widest range in whole-tree density within an age-class; for example in a 13-year-old stand, five individual trees ranged in density from 338 kg/m^3 to 628 kg/m^3. Sampling additional trees around 10 years of age and in the 20- to 30-year age group would strengthen the age-density relationship. *Acacia dealbata* has rapidly increasing density with age, taking it from a low-density species when young to a high-density one with age.

Acacia mearnsii

A total of 21 trees from the Bay of Plenty region, aged 2 years, 4 years, and approximately 14 years, were studied for *A. mearnsii*. It was difficult to count growth rings for the oldest stand and a best estimate combined with approximate planting date indicated an age of 14 years. More sample trees for whole-tree density are required across all ages. *Acacia mearnsii* is remarkable for both rapid growth and high density when young.

Cypresses

As in Table 1, the four cypress species have been amalgamated into one group to yield a database of 119 trees, ranging in age from 13 years to 52 years. *Chamaecyparis lawsoniana* constituted most of this data, with 85 trees studied from ages 13 to 52 years; *C. lusitanica* constituted most of the rest, with 30 trees aged 43 years averaging 413 kg/m^3. Density showed no increase with age for *Ch. lawsoniana* and all species averaged 418 kg/m^3 across all age-classes.

Pseudotsuga menziesii

The *Ps. menziesii* data set comprised a substantial total of 232 trees, ranging in age from 27 to 62 years. All the stands in the eight age-classes represented were from either Kinleith or Kaingaroa Forest. There was little increase in density from age 27 years but more trees need to be sampled to determine the pattern when young. Above age 27 years, density averaged 406 kg/m^3 across all ages.

Eucalyptus fastigata

Eucalyptus fastigata had the second largest data set of the 16 species studied, with a total of 160 trees, aged from 2 to 43 years. Ninety-nine selected trees from two sites (Kaingaroa and Kinleith), aged 17 years, represented much of the density database and more trees need to be sampled in the <7, 8–12, and >18-year age-classes. This species, a member of the ash group like *E. regnans*, is of relatively low density.

Eucalyptus globoidea

For *E. globoidea*, five trees were sampled for density from each of three stands aged 15 years, 35 years, and 40 years, located in the Coromandel and coastal Bay of Plenty at Tairua, Matakana Island, and Whakatane, with a further nine trees aged 60 years at Matakana Island. To improve the age-density relationship, the mean outerwood increment core density for 21, 7-year-old trees from Titoki in Northland was included as a single data point. More data, particularly from younger-aged stands, are needed to predict the age-density relationship for this species reliably. *Eucalyptus globoidea* and *E. muelleriana* are from the same stringybark group, also closely related to *E. pilularis,* and all are characterised by high wood density, as well as good sawing properties and natural durability.

Eucalyptus globulus

Thirty trees were sampled from two sites in Northland and one site near Napier on the East Coast, at ages 8 and 11 years, and some were chipped for a recent kraft pulping study. The relationship between age and density could not be properly estimated for this species as only 8- and 11-year-old trees were sampled. Density of *E. globulus* was much higher than that of *E. nitens* and was approximately 70 kg/m^3 lower than that of the closely-related *E. maidenii.*

Eucalyptus maidenii

Thirty trees were sampled from two sites in Northland and one site near Napier on the East Coast, at ages 8 and 11 years, and some were chipped for a recent kraft pulping study. The relationship between age and density could not be properly estimated for this species. Density of *E. maidenii* was much higher than that of *E. nitens* and was also higher than that of the closely-related *E. globulus*.

Eucalyptus muelleriana

A total of 15 trees of *E. muelleriana* were sampled for whole-tree density, from stands aged 15 and 45 years from Tairua and Athenree respectively in the western Bay of Plenty. Average outerwood increment core densities for 6- and 7-year-old trees from Parakao and

Titoki in Northland (120 and 20 trees respectively) were included as two data points to improve the age-density relationship. The density gradient between ages 15 and 45 years appeared relatively flat for this species, in contrast to the related *E. globoidea* and *E. pilularis*.

Eucalyptus nitens

One hundred and one trees, aged 2–30 years, comprised the whole-tree density database for this species. Sites ranged from Kaikohe in Northland to Canterbury. Mean whole-tree density increased from 382 kg/m^3 (aged 2 years) to 598 kg/m^3 (aged 30 years). Even in this relatively well-sampled species, poor representation of the older age-classes and high variability between trees reduced precision of the regression.

Eucalyptus pilularis

Whole-tree density information for this species was from 20 trees, aged 15 years, from a site at Tairua on the Coromandel Peninsula. Density ranged from 499 kg/m^3 to 670 kg/m^3. Future sampling at a minimum of two contrasting ages (approximately 5 to 10 years and 20 to 25 years) would establish a whole-tree density/age regression for this species. The mean outerwood increment core density for 21, 7-year-old trees from Titoki in Northland was included as a single data point to provide some indication of the age-density relationship.

Eucalyptus regnans

A large data set was available for this species, with over 140 trees mainly from the central North Island and from one South Island site. Age was 2–70 years, with most of the samples aged 5–21 years. This was the lowest-density eucalypt species sampled, with a density of only 445 kg/m^3 at age 21 years.

Eucalyptus saligna

Six stands were sampled, aged 2–45 years, located mainly in the central North Island region, with one site in the northern South Island. Future sampling should be concentrated on the 10- to 20-year age bracket. *Eucalyptus saligna* was one of the highest density eucalypts sampled, with a wide range of age-classes.

Comparison of Regressions of Density on Age among Species

The regression lines for whole-tree basic density with age for all species and species groups included in this study are shown in Fig. 2. Despite the limited amount of data for some species, this graph provides a good picture of differences in whole-tree wood density development with age, in widely differing species. The two extremes amongst the hardwoods were *E. regnans* with some of the lowest whole-tree densities, even at 70 years of age, and *A. mearnsi* with the highest whole-tree densities of any species at 14 years of age. The softwoods, *Ps. menziesii* and the cypresses, showed much lower whole-tree densities, which increased little from age 15 years. The eucalypts could be grouped into low density (*E. regnans, E. fastigata*, and *E. nitens*) and high density (*E.muelleriana, E. saligna, E. globoidea, E. pilularis*, and *E. maidenii*). The two acacias had contrasting densities, with *A. mearnsii* rapidly reaching very high density and *A. dealbata* increasing density more gradually with age.

CONCLUSIONS AND RECOMMENDATIONS

This study highlighted the wide range in basic wood density of whole trees amongst some fast-grown hardwood and softwood species in New Zealand. It also showed up the gaps in knowledge of basic density at different ages for these species. This information may be used to plan future collection of stem-disc material for certain species.

Perhaps the most remarkable feature of these results is that the density trends with age were as clear as they were. Fortunately, the environmental variation between sites in climate and soil, which was often confounded with age-class of the material, did not make this relationship impossible to estimate. Variation in whole-tree density between trees of a species within a site and within age-classes was large for all species, typically 70–90 kg/m^3 for eucalypts (*E. muelleriana* was unusually low at 47 kg/m^3). *Pseudotsuga menziesii* and the cypresses showed large between-tree variation within stands, averaging 95 kg/m^3 in stands with species means of only 406 and 418 kg/m^3 respectively. *Acacia dealbata* had an average range within age-classes of 184 kg/m^3. Standard deviations of whole-tree density within age-class were typically from 20 to 40 kg/m^3 for the eucalypts, cypresses, and *Ps. menziesii.*

The species that were selected for study were all relatively fast-grown and/or commercially planted. Among the eucalypts, predicted mean whole-tree density at age 30 years varied from 452 kg/m^3 for *E. regnans* to 623 kg/m^3 for *E. globoidea*. No data were available for *Acacia mearnsii* beyond age 14 years, but at this age density was higher than that of *E. globoidea*. The two softwoods showed much lower densities at age 30 years than the hardwoods, with 406 kg/m^3 for *Ps. menziesii* and 418 kg/m^3 for the cypresses.

Once relationships of whole-tree basic density with breast-height core outerwood density have been determined, increment-core data, which are more readily available than disc data, can be used to strengthen the density-age relationships presented here. It is recommended that species/age-classes should be listed where there is little whole-tree density information, so that a programme of disc sampling for each species can be planned.

In this study there was unavoidable confounding of the effects of site and age-class, as well as genetic effects of provenance or seedlot, and it is desirable to disentangle these. This could be done by further sampling of known seedlots of the most important species at different sites and ages. This is planned for *E. nitens,* and will allow these effects to be evaluated. However, the most precise yet most costly and long-term method of studying these relationships is to plant species and provenance trials on several different sites and to sample these destructively at an advanced age.

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REFERENCES

BERRILL, J-P.; McKINLEY, R.B.; SHELBOURNE, C.J.A.: Comparison of volume yields and stem dry matter production of alternative species (in prep.)

COWN, D.J. 1999: New Zealand pine and Douglas-fir: Suitability for processing. *New Zealand Forest Research Institute, Forest Research Bulletin No.216.*

FREDERICK, D.J.; MADGWICK, H.A.I.; OLIVER, G.R. 1982: Wood basic density and moisture content of young *Eucalyptus regnans* grown in New Zealand. *New Zealand Journal of Forestry Science 12(3)*: 494–500.

JANSEN, G.R. 1998: Wood density and biomass evaluation of *Eucalyptus nitens, E. globulus* and *E. maidenii* on two sites. B.Sc. (Technology Industry Report, University of Waikato, Hamilton, New Zealand.

KIBBLEWHITE, R.P. 1999: Designer fibres for improved papers through exploiting genetic variation in wood microstructure. *Appita 52(6)*: 429–440.

KIBBLEWHITE, R.P.; SHELBOURNE, C.J.A. 1997: Genetic selection of trees with designer fibres for different paper and pulp grades. Proceedings of 11th Fundamental Research Symposium, Cambridge.

KIBBLEWHITE, R.P.; JOHNSON, B.I.; SHELBOURNE, C.J.A. 2000: Kraft pulp qualities of *Eucalyptus nitens, E. globulus*, and *E. maidenii*, at ages 8 and 11 years. *New Zealand Journal of Forestry Science 30(3)*: 447–457.

LAUSBERG, M.J.F.; GILCHRIST, K.F.; SKIPWITH, J.H. 1995: Wood properties of *Eucalyptus nitens* grown in New Zealand. *New Zealand Journal of Forestry Science 25(2)*: 147–163.