Variation in basic wood density and percentage heartwood in temperate Australian *Acacia* species

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Summary

Species, provenance and within-tree variation in basic wood density and percentage heartwood were assessed in 18 tree-form *Acacia* species/subspecies (40 provenances) and *Eucalyptus nitens* (one provenance) from southern Australia. The 229 trees from two 8-y-old trials in the Australian Capital Territory were destructively sampled.

Whole-tree, volume-weighted basic wood densities for the *Acacia* species were between 568 and 771 kg m^{-3} and provenance means were in the range 520–778 kg m^{-3}. Percentage heartwood, sampled at 20% of tree height, ranged between 2.4 and 43.8% for species and 0.0 and 44.1% for provenances.

There were highly significant differences ($P < 0.001$) between *Acacia* species for basic wood density, the trend in basic density with tree height, and percentage heartwood. Provenance variation in *Acacia mearnsii* in basic density and percentage heartwood, and in *A. silvestris* for basic density, was significant ($P < 0.05$) and could be exploited in breeding programs.

There was some association between basic density and percentage heartwood at the species level, but no association at the provenance within species level.

Keywords: species trials; provenance trials; genetic variation; wood properties; wood density; heartwood; *Acacia*; *Acacia mearnsii*; *Acacia silvestris*; *Eucalyptus nitens*

Introduction

Acacias that grow naturally in the cooler and often moister parts of eastern and south-eastern Australia are referred to as 'temperate' acacias in this paper. Some of these temperate acacias are used for a range of commercial wood purposes; from firewood to charcoal, paper, panels and high quality furniture. Descriptions of their wood densities and heartwood characteristics and how these change with tree age, within the tree and with growth conditions are generally limited or unavailable. Even for *Acacia mearnsii* (black wattle), grown extensively in commercial plantations in several countries for more than a century, basic densities are invariably reported for trees of unspecified age. These reports differ significantly, for example 630 kg m^{-3} (Bootle 1983), 530–598 kg m^{-3} (Hillis 1997) and 550–850 kg m^{-3} (Dobson and Feely 2002).

A few *Acacia* species and provenance trials planted in southern Australia in the 1990s have been assessed for wood density (either basic, air-dry or green) at a particular age and the sampling strategy has been described (Barbour 2000; Clark 2001). One of the difficulties in comparing such density data, when they are available, is that they have frequently been collected using different procedures for within-tree and within-population sampling (Balodis 1994; Downes *et al*. 1997; Ilic *et al.* 2000).

Basic wood density influences both the paper-making process and the properties of paper (Malan and Arbuthnot 1995), and is an important economic indicator of pulpwood quality (Balodis 1994). For pulp and paper manufacture, wood in the basic density range of 400–600 kg m^{-3} is preferred (Downes *et al.* 1997) and species such as *A. mearnsii*, *A. dealbata*, *A. decurrens* and *A. silvestris* have been shown to produce good quality pulpwood with high kraft yield, low pulping chemical usage and good paper strength properties (Fang *et al.* 1991). Although there are no commercial plantations of these species in Australia, *A. mearnsii* and *A. dealbata* harvested from native forests have been included in woodchip exports to Japan.

In South Africa, *A. mearnsii* timber is in demand as a source of high-quality fibre (Dobson and Feely 2002) for dissolving pulp manufacture to produce rayon domestically and for export to kraft pulp mills for paper production in Japan. For example, since the mid-1990s a clear premium has been paid for plantation-grown *A. mearnsii* compared to eucalypt chips from plantations in South Africa or native eucalypt chips from Australia (e.g. Jaakko Pöyry Consulting 1999; Dunlop *et al.* 2000).

Basic density is also used to estimate carbon stored in the woody stems of trees (Ilic *et al.* 2000) and has an appreciable influence on many solid wood properties and conversion processes, including cutting, gluing, finishing, rate of drying and paper making. It provides a good but not always direct indication of the strength, stiffness and toughness of timber (Hillis 1978). In general, the denser the wood of a species, the greater the mechanical properties of its clear timber (Bootle 1983). Temperate acacias such as *A. mearnsii* have also been used for round timber purposes such as fence posts and building poles in South Africa (Dobson and Feely 2002) and as preservative-treated vineyard posts in Australia (Bird 2000). High basic density is a useful criterion for predicting fuelwood properties. High-density wood generates more heat per unit volume and is therefore better in a practical sense for storage, handling and transport purposes (Groves and Chivuya 1989).

Heartwood, the innermost and older wood within a tree, is often characterised by deposits of resinous, phenolic and other compounds which contribute considerably to the colour of the wood. These deposits are also mainly responsible for the enhanced durability of heartwood (Bootle 1983; Boland *et al*. 1984). Species with attractive heartwood colour and grain generally attract the highest returns, as they are used for the highest value products — including structural and decorative timbers for building, joinery and furniture (Reid 1995; Bird 2000). Some Australian acacias, such as *A. melanoxylon* (blackwood), are valued for their attractive heartwood but little research has been conducted to understand the genetic variation of this characteristic as the basis for tree improvement (Searle 2000).

Commercial plantations of temperate Australian acacias are in their infancy in Australia. The timber of *A. melanoxylon* and *A. dealbata,* used for furniture and cabinet manufacture in Australia, continues to be harvested from natural stands, although its continued availability from state-owned land is not assured. The suitability of temperate acacias for niche products such as preservative-treated trellis posts for vineyards (Mollah *et al*. 2004), and charcoal and activated carbon (Bartle *et al.* 2002) is being explored. If commercial plantations are to be established with genetically improved stock it will be essential to understand the variation in wood properties within and between species.

The aim of this study was to compare the whole-tree, volume-weighted basic density and cross-sectional area of heartwood (at 20% tree height) of 18 temperate Australian *Acacia* species/subspecies and a commercial eucalypt species, all of known age and genetic origin under cultivation, at 8 y of age. The significance of the genotype × environment interaction in basic density and percentage heartwood between *A. mearnsii*, *A. decurrens* and *Eucalyptus nitens* across two sites was also examined.

Materials and methods

Background to field trials

The two trials sampled for this study were planted in October 1994 as part of an international series of temperate acacia field trials part-funded by the Australian Centre for International Agricultural Research through the project 'Australian acacias for sustainable development in China, Australia and Vietnam'. The trials were planned and established by CSIRO Forestry and Forest Products and partners in the three countries.

The purpose of the project in Australia was to identify productive *Acacia* species for farm forestry and plantations. Most acacias selected for these trials are closely related to the multipurpose and commercially successful *A. mearnsii* and are bipinnate species in the Section Botrycephalae of the genus *Acacia* (Boland 1987). The three *Acacia* species in this study not in this taxonomic group were *A. implexa*, *A. melanoxylon* (both known for their attractive heartwood), and *A. binervia* (initially selected for possible frost tolerance).

Eucalyptus nitens, a native species used for structural and appearance-grade timbers and planted for paper pulp in Tasmania (Boland *et al.* 1984; Eldridge *et al.* 1994) was included for comparison in this study as it was one of the best performers in earlier species elimination trials in the Canberra region (Clarke *et al.* 1997).

Trial sites

The Uriarra Forest Settlement trial is located 19 km west of Canberra, ACT (latitude 35°18′S, longitude 148°56′E, altitude 618 m above sea level) on a red podzolic soil (replicates 2, 3 and 4) and a deep yellow earth (replicate 1) derived from Paddys River volcanics. The site has a mean annual rainfall of 824 mm. The second trial is at Kowen, located 12 km east-south-east of Canberra (latitude 35º20′S, longitude 149º15′E, altitude 585 m a.s.l.). It is on a red podzolic soil derived from old river terrace gravels over Ordovician sediments. This site has a mean annual rainfall of 630 mm.

Experimental design

Both trials originally included the same 25 acacias and one eucalypt (*E. nitens*) represented by 64 provenances arranged in a square lattice (8 × 8) with four replicates in an incomplete block design. Each provenance was represented by 40 trees in each trial and each plot included 10 trees arranged in two rows of five trees at 2.5 m × 3.0 m spacing. Both trials were surrounded by two rows of buffer trees to minimise edge effects (Searle *et al.* 1998).

Sampling in the trials

One eucalypt species and 21 *Acacia* species/subspecies (43 acacia provenances — see Table 1) represented by 211 8-y-old trees were sampled from the Uriarra trial between June and November 2002. In January 2003 the Uriarra trial was seriously damaged by a major bushfire.

Twenty-four trees were sampled in the Kowen trial in December 2002, at age 8 y and 2 mo. Six trees from each of four provenances were felled to represent *A. mearnsii* (two provenances), *A. decurrens* (one provenance) and *E. nitens* (one provenance).

The trees were sampled according to a protocol developed for eucalypts (Downes *et al.* 1997) based on the number of trees required to estimate the mean basic density with an accuracy of ± 5%. A minimum of six trees was suggested to account for between-tree variation in wood density. We therefore destructively sampled six trees from each of the provenances that met the sampling criteria.

Although the plots at Uriarra were not chosen at random (the sampling began at replicate 1 and continued systematically to replicates 2, 3 and 4 until six trees from each provenance had been sampled where possible) the trees within plots were chosen randomly if they were relatively undamaged by birds (cockatoos), had no more than two stems, and stem diameters of ≥ 6 cm at breast height (1.3 m). A maximum of three trees was sampled

Table 1. Seedlots sampled from eight-year-old species/provenance trial at Uriarra near Canberra (ACT)

Treat. no.	Species	Common name	Seedlot[1]	Location	Lat.	Long.	Alt. (m a.s.l.)
44	*Acacia binervia*	Coast myall	15845	Richmond-Springwood NSW	33°38′E	150°40′S	15
6	*A. blayana*	Blay's wattle	18068	Brogo NSW	36°29′E	149°40′S	500
7	*A. dangarensis*	None	18608	Mt Dangar NSW	32°20′E	150°28′S	600
8	*A. dealbata*	Silver wattle	18024	Captains Flat NSW	35°37′E	149°26′S	700
32	*A. dealbata*		16271	Errinundera Plateau Vic.	37°11′E	148°52′S	960
1	*A. dealbata*		18973	Kandos, 4 km E Lithgow NSW	32°56′E	149°54′S	600
2	*A. deanei*	Deane's wattle, green wattle	15470	Goondiwindi NSW	28°49′E	150°43′S	260
58	*A. decurrens*	Black wattle, green wattle	14726	SW Goulburn NSW	34°53′E	149°17′S	685
26	*A.* ***decurrens***[2]		**15847**	**Picton-Mittagong NSW**	**34°17′E**	**150°35′S**	**380**
61	*A. falciformis*	Broad-leaf hickory	16253	11 km WNW Narooma NSW	36°11′E	150°01′S	150
31	*A. filicifolia*	Fern-leaf wattle	15841	19 km SW Singleton NSW	32°41′E	151°01′S	150
34	*A. filicifolia*		17893	Yadboro Flat NSW	35°19′E	150°14′S	60
60	*A. fulva*	Soft wattle	15843	Howes Valley NSW	32°52′E	150°52′S	240
56	*A. fulva*		18972	Mt Yengo NSW	32°59′E	150°51′S	600
42	*A. glaucocarpa*	None	15473	c. 20 km NW Gayndah Qld	25°32′E	151°29′S	390
24	*A. glaucocarpa*		18065	Cadarga Qld	26°07′E	150°55′S	350
45	*A. implexa*	Hickory wattle, lightwood	18019	Pyalong Vic.	37°08′E	144°53′S	200
13	*A. implexa*		18611	Sofala NSW	33°11′E	149°41′S	850
10	*A. irrorata* ssp. *irrorata*	Green wattle, blueskin	15840	Craven-Stroud NSW	32°10′E	151°57′S	110
40	*A. irrorata* ssp. *irrorata*		18626	Gloucester NSW	31°59′E	151°47′S	650
16	*A. irrorata* ssp. *irrorata*		18619	Bodalla NSW	36°08′E	150°02′S	20
9	*A. irrorata* ssp. *velutinella*	None	18623	Congarinni State Forest NSW	30°41′E	152°53′S	60
47	*A. leucoclada* ssp. *leucoclada*	Northern silver wattle	18621	Inverell NSW	29°44′E	150°57′S	700
63	*A. leucoclada* ssp. *argentifolia*	None	18067	Dalveen-Warwick Rd Qld	28°23′E	151°55′S	750
59	*A. mearnsii*	Black wattle, green wattle	18977	Mt Gladstone, W Cooma NSW	39°15′E	149°05′S	1000
53	*A. mearnsii*		15329	Apsley R, W Bicheno Tas.	41°56′E	148°14′S	10
38	***A. mearnsii***		**17933**	**Wattle Circle, Omeo Hwy Vic.**	**37°27′E**	**147°50′S**	**200**
50	***A. mearnsii***		**18979**	**Blackhill Reserve, NE Kyneton Vic.**	**37°12′E**	**144°29′S**	**520**
18	*A. mearnsii*		18975	N Bungendore NSW	35°11′E	149°32′S	760
17	*A. mearnsii*		16621	Tuross R, SW Bodalla NSW	36°11′E	149°58′S	15
14	*A. melanoxylon*	Blackwood	16358	Bli Bli Qld	26°37′E	153°02′S	95
35	*A. melanoxylon*		18981	Grampians National Park Vic.	37°22′E	142°31′S	300
36	*A. melanoxylon*		18980	Gellibrand R. Vic.	38°43′E	143°15′S	50
28	*A. melanoxylon*		16526	25 km SE Mt Gambier SA	37°57′E	141°56′S	40
30	*A. melanoxylon*		15863	Blackwood Park, Lileah Tas	40°57′E	145°10′S	250
4	*A. parramattensis*	Sydney green wattle, Parramatta wattle	17925	Numeralla NSW	36°11′E	149°18′S	900
11	*A. parramattensis*		17711	Tarago NSW	35°10′E	149°35′S	740
19	*A. parvipinnula*	Silver-stemmed wattle	15842	Howes Valley NSW	32°52′E	150°52′S	240
62	*A. silvestris*	Red wattle, Bodalla silver wattle	17939	Bruthen Vic.	37°35′E	147°54′S	200
21	*A. silvestris*		16254	11 km WNW Narooma NSW	36°11′E	150°01′S	130
25	*A. silvestris*		15852	Deua R, Deua National Park NSW	35°58′E	149°45′S	350
27	*A. trachyphloia*	Golden feather wattle	14229	Monga State Forest NSW	35°36′E	149°55′S	710
48	*A. trachyphloia*		17894	Currowan Ck. NSW	35°35′E	150°03′S	100
3	***Eucalyptus nitens***	**Shining gum**	**14438**	**Badja State Forest NSW**	**36°01′E**	**149°34′S**	**1050**

[1]CSIRO Australian Tree Seed Centre seedlot numbers [2]Bolded species were also sampled at Kowen.

from any one plot to ensure that the six trees were sampled from at least two replicates.

At Kowen, 24 trees from four provenances were sampled to represent three species that were chosen to compare and contrast wood density values between the two sites. Replicates 1, 3 and 4 were sampled. (Replicate 2 had poor survival and was excluded from the sampling.)

Sampling within trees

Whole-tree density was calculated as a volume-weighted average of the density at eight points within the stem (Downes *et al.* 1997). Diameter at breast height over bark (dbhob) was measured for each tree and after felling, the total tree length was measured. Eight cross-sectional discs were cut from each tree at 2%, 10%, 20%, 30%, 40%, 50%, 60% and 70% of tree height and labelled.

The discs were debarked the same day and the diameter under bark was measured.

The cross-sectional width of the heartwood of the sample taken at 20% tree height was also measured (the average of two measurements; taken first at the largest width and then at 90° to the first measurement). The samples were then soaked in water for at least two days before being weighed for the first time.

Measurement and calculation of whole-tree basic wood density

Disc samples were weighed three times to determine their basic density (bone-dry weight per unit of maximum volume) using TAPPI standard T 258 om-89 — the water immersion method. They were weighed for their green (maximum/water-soaked) weight; green volume measured using the suspended submergence method for volume determination and dry weight after drying at 105°C to constant weight. The volume-weighted mean density of each tree was calculated from the dimensions of the eight green discs and their basic densities.

Statistical analyses

Insufficient samples were collected from *A. deanei*, *A. falciformis* and *A. irrorata* subsp. *velutinella* and these species were excluded from the analysis of variance that was conducted for a total of 205 trees that represented 18 *Acacia* species/subspecies (represented by 40 provenances) and *E. nitens* (1 provenance).

Preliminary calculations were made for volume (under bark) and basic density for each tree using Microsoft Office XP Excel. This program was also used to calculate the average area of heartwood of the discs sampled at 20% tree height; convert it to a percentage of the total cross-sectional area of the disc and then transform it to a radian angle to satisfy the assumptions of the analysis. The data were analysed using the procedure in the statistical package GENSTAT (Release 4.2) for the analysis of unbalanced data.

As there were large differences in the number of trees sampled (i.e. from 5 to 33) for each species/subspecies in the Uriarra trial, standard errors of differences between means differed greatly. Therefore individual t-tests were used to examine the significance of variation between pairs of species means at the 5% probability level for basic density, percentage heartwood and the general trend in basic density with tree height (the regression coefficient or slope of the regression line for a regression analysis of basic density versus percentage tree height). We recognise that using pairwise t-tests may lead to an overestimation of significance levels.

The significance of variation between provenance means within two species (*A. mearnsii* and *A. silvestris)* for basic density, percentage heartwood and trend in basic density with percentage tree height was examined using a t-test at the 5% probability level.

Covariance analysis for percentage heartwood and basic density, height, diameter (dbhob), volume and trend in basic density with percentage tree height was used to determine if there were any associations between these characteristics at the species level.

Genotype × environment interactions

The purpose of the smaller sampling of species/provenances at Kowen was to determine if there were any significant genotype × environment interactions for basic density and percentage heartwood between trees grown at the two sites.

Three of the same species/provenances sampled at Uriarra were also sampled at Kowen: *A. mearnsii* (two provenances; S17933 Wattle Circle, Omeo Hwy, Victoria; S18979 Blackhill Reserve, Kyneton, Victoria), *A. decurrens* (S15847 Picton-Mittagong, New South Wales) and *E. nitens* (S14438 Badja State Forest, New South Wales).

The plot means from the two trials were combined for an analysis across sites to examine the significance of genotype × environment interaction effects for basic density and percentage heartwood.

Results

Uriarra

Variation in basic density between species

Species means for growth (height, diameter and volume), trend in basic density with height, percentage heartwood and whole-tree, volume-weighted basic density at Uriarra and Kowen are presented in Table 2.

All the acacias in this study were denser than the *E. nitens* and had mean whole-tree, volume-weighted basic densities greater than 500 kg m^{-3}. There were no significant differences for basic density between replicates in the Uriarra trial, but there were highly significant differences for basic density ($P < 0.001$) between species. (See Table 3 where the results of individual t-tests are presented together in the one table in the same way as a multiple range test.) Values for the *Acacia* species ranged from 568 kg m^{-3} for *A. trachyphloia* to 771 kg m^{-3} for *A. fulva*. A couple of anomalies in the presentation of the significance of differences between species for mean basic wood density did occur as a result of the unequal number of trees sampled per species/subspecies (Table 3).

Acacia trachyphloia had the lowest mean for whole-tree, volume-weighted basic density (568 kg m^{-3}) among the acacias. Species with the lowest density were *E. nitens, A. trachyphloia, A. dealbata* and *A. melanoxylon* (530–576 kg m^{-3}). The other 14 *Acacia* species were significantly denser than *E. nitens* (Table 3). *Acacia fulva, A. dangarensis* and *A. leucoclada* (both subsp. *leucoclada* and subsp. *argentifolia*) with species means ranging from 771 to 724 kg m^{-3} were the densest species in the trial and did not differ significantly from each other. *Acacia mearnsii* (six provenances) had a mean basic density of 663 kg m^{-3}.

Variation in basic density between provenances

Predicted provenance means (adjusted for replicates) for tree height, diameter (dbhob), volume, trend in basic density with tree

Table 2. Basic statistics including mean values for species sampled in descending order of basic wood density

Location and species	No. of provenances	No. of trees sampled	Diameter at breast height over bark (cm)	Height (m)	Volume under bark (m^3)	Trend in basic density with height[1]	Heartwood (%)	Basic wood density[2] (kg m^{-3})
Uriarra								
Acacia fulva	2	12	10.3	8.2	0.026	–0.0090	34.5	771
A. dangarensis	1	6	7.2	6.0	0.011	–0.0142	43.8	752
A. leucoclada ssp. *leucoclada*	1	7	8.4	7.8	0.019	0.0080	18.4	728
A. leucoclada ssp. *argentifolia*	1	6	8.2	8.0	0.018	0.0004	18.0	719
A. glaucocarpa	2	12	10.2	8.7	0.028	–0.0084	27.5	701
A. parramattensis	2	6	9.3	7.5	0.020	–0.0122	13.6	687
A. filicifolia	2	12	11.4	7.6	0.030	0.0034	23.0	680
A. parvipinnula	1	5	8.5	7.7	0.018	–0.0153	20.1	680
A. implexa	2	12	7.9	6.4	0.010	–0.0083	42.1	668
A. mearnsii	**6**	**33**	**11.6**	**8.6**	0.039	**–0.0190**	**13.2**	**663**
A. blayana	1	6	10.8	7.9	0.033	–0.0104	9.8	663
A. silvestris	3	18	9.6	8.2	0.028	–0.0028	16.8	654
A. decurrens	**2**	**12**	**13.1**	**9.0**	0.052	**–0.0095**	**21.2**	**647**
A. binervia	1	6	8.2	6.9	0.015	–0.0112	13.6	645
A. irrorata ssp. *irrorata*	3	12	10.3	7.2	0.026	–0.0239	6.7	623
A. melanoxylon	5	17	8.7	5.6	0.016	–0.0058	2.4	576
A. dealbata	3	10	12.2	7.7	0.042	0.0115	9.3	570
A. trachyphloia	2	7	9.8	7.4	0.026	0.0101	6.4	568
Eucalyptus nitens	**1**	**6**	**17.3**	**11.0**	0.089	**0.0200**	**19.1**	**530**
Kowen								
A. decurrens	1	6	11.8	7.8	0.034	—	22.9	667
A. mearnsii	2	12	13.1	8.4	0.048	—	17.5	666
E. nitens	1	6	15.3	9.3	0.069	—	2.6	556

[1]Linear regression coefficient on % tree height
[2]Whole-tree, volume-weighted mean basic density

Table 3. Basic wood density — mean values and the significance of differences based on pairwise t-tests at the 5% significance level, Uriarra

Species	No. of trees sampled	Basic wood density (kg m^{-3})	Significance of differences[1]						
Acacia fulva	12	771	a						
A. dangarensis	6	752	a	b					
A. leucoclada ssp. *leucoclada*	7	728	a	b	c				
A. leucoclada ssp. *argentifolia*	6	719	a	b	c	d			
A. glaucocarpa	12	701		b	c	d			
A. parramattensis	6	687		b	c	d	e		
A. parvipinnula	5	680		b	c	d	e		
A. filicifolia	12	680			c	d	e[2]		
A. implexa	12	668			c	d	e		
A. blayana	6	663			c	d	e		
A. mearnsii	33	663				d	e		
A. silvestris	18	654				d	e		
A. decurrens	12	647				d	e		
A. binervia	6	645				d	e	f	
A. irrorata ssp. *irrorata*	12	623					e	f	
A. trachyphloia	7	568						f	g
A. melanoxylon	17	576							g
A. dealbata	10	570							g
Eucalyptus nitens	6	530							g

[1]Species means with the same letter did not differ significantly
[2]*A. filicifolia* and *A. irrorata* ssp. *irrorata* were just significantly different at the 5% probability level ($P \approx 0.04$)

Table 4. Basic statistics including mean values for provenances sampled for Uriarra and Kowen, ACT in descending order of basic wood density

Location and treat. no.	Species	No. of trees sampled	Height (m)	Dbhob (cm)	Vol. (ub) (m^3)	Trend in basic density with height[1]	Heartwood (%)	Basic wood density[2] ($kg\ m^{-3}$)
Uriarra								
56	*Acacia fulva*	6	8.2	10.2	0.026	–0.0115	32.1	778
60	*A. fulva*	6	8.3	10.4	0.026	–0.0064	37.2	764
7	*A. dangarensis*	6	6.0	7.2	0.011	–0.0142	43.8	752
62	*A. silvestris*	6	7.0	6.8	0.014	–0.0016	12.9	731
47	*A. leucoclada* ssp. *leucoclada*	7	7.8	8.4	0.019	0.0080	18.4	728
38	***A. mearnsii***	**6**	**8.6**	**11.1**	0.035	**–0.0167**	**12.3**	**726**
63	*A. leucoclada* ssp. *argentifolia*	6	8.0	8.2	0.018	0.0004	18.0	719
34	*A. filicifolia*	6	7.1	11.4	0.030	0.0081	18.8	715
42	*A. glaucocarpa*	6	8.5	9.8	0.028	–0.0105	28.6	707
4	*A. parramattensis*	3	7.2	8.6	0.016	–0.0116	13.8	705
24	*A. glaucocarpa*	6	8.9	10.5	0.029	–0.0063	26.4	695
13	*A. implexa*	6	7.2	8.4	0.012	0.0019	39.5	686
19	*A. parvipinnula*	5	7.7	8.5	0.018	–0.0153	20.1	680
11	*A. parramattensis*	3	7.7	9.8	0.023	–0.0126	13.4	676
26	***A. decurrens***	**6**	**8.9**	**12.2**	0.047	**–0.0081**	**14.8**	**664**
59	*A. mearnsii*	6	8.6	11.0	0.033	–0.0146	11.3	664
6	*A. blayana*	6	7.9	10.8	0.033	–0.0104	9.8	663
45	*A. implexa*	6	5.9	7.5	0.090	–0.0159	44.1	655
10	*A. irrorata* ssp. *irrorata*	2	6.3	8.3	0.015	–0.0314	32.9	654
50	***A. mearnsii***	**6**	**8.9**	**13.5**	0.052	**–0.0207**	**18.7**	**651**
18	*A. mearnsii*	6	7.9	11.1	0.036	–0.0210	7.6	651
31	*A. filicifolia*	6	8.0	11.4	0.029	–0.0013	26.6	645
53	*A. mearnsii*	5	7.8	11.4	0.033	–0.0203	18.9	645
44	*A. binervia*	6	6.9	8.2	0.015	–0.0112	13.6	645
40	*A. irrorata* ssp. *irrorata*	6	8.0	11.1	0.030	–0.0168	9.6	644
58	*A. decurrens*	6	9.1	14.0	0.057	–0.0110	28.5	630
48	*A. trachyphloia*	3	8.0	9.1	0.027	0.0082	8.1	627
21	*A. silvestris*	6	9.8	12.1	0.043	0.0018	22.7	621
17	*A. mearnsii*	4	9.0	10.5	0.033	–0.0230	12.7	613
35	*A. melanoxylon*	5	5.4	7.5	0.011	–0.0098	0.0	613
25	*A. silvestris*	6	8.1	10.5	0.031	–0.0077	16.5	602
8	*A. dealbata*	6	7.4	10.5	0.033	0.0130	9.0	585
16	*A. irrorata* ssp. *irrorata*	4	6.3	9.4	0.022	–0.0330	1.3	585
28	*A. melanoxylon*	3	5.2	10.4	0.020	0.0112	7.3	569
27	*A. trachyphloia*	4	7.3	9.9	0.026	0.0104	6.1	558
14	*A. melanoxylon*	2	6.6	10.0	0.022	–0.0039	10.3	548
36	*A. melanoxylon*	5	5.9	8.8	0.018	–0.0146	2.0	542
1	*A. dealbata*	1	8.3	15.5	0.054	0.0088	11.3	538
3	***Eucalyptus nitens***	**6**	**11.0**	**17.3**	0.089	**0.0200**	**19.1**	**530**
32	*A. dealbata*	1	9.7	18.1	0.097	0.0055	3.0	525
30	*A. melanoxylon*	2	5.6	8.9	0.019	–0.0044	19.6	520
Kowen								
38	*A. mearnsii*	6	8.5	12.5	0.046		15.5	688
26	*A. decurrens*	6	7.8	11.8	0.034		22.9	667
50	*A. mearnsii*	6	8.2	13.7	0.049		19.6	645
3	*E. nitens*	6	9.3	15.3	0.069		2.6	556

[1]Linear regression coefficient on % tree height
[2]Whole-tree, volume-weighted mean basic density

height, percentage heartwood and whole-tree, volume-weighted basic density are presented in Table 4.

Whole-tree, volume-weighted mean basic densities for acacia provenances ranged from 520 to 778 kg m^{-3}. Provenances of *A. melanoxylon* (S15863 Blackwood Park, Lileah, Tas., 520 kg m^{-3}), *A. dealbata* (S16271 Errinundera Plateau, Vic., 525 kg m^{-3}) and *E. nitens* (S14438 Badja State Forest, NSW, 530 kg m^{-3}) had the lowest basic densities while 31 of the 40 acacia provenances

Table 5. Species trends in basic wood density with tree height expressed as linear regression on percentage tree height — mean values and the significance of differences based on pairwise t-tests at the 5% significance level, Uriarra

Species	Trend in basic density with tree height	Significance of differences[1]
Eucalyptus nitens	0.0200	a
Acacia dealbata	0.0115	a b
A. trachyphloia	0.0101	a b c
A. leucoclada ssp. *leucoclada*	0.0080	a b c
A. filicifolia	0.0034	b c d
A. leucoclada ssp. *argentifolia*	0.0004	b c d e
A. silvestris	–0.0028	c d e
A. melanoxylon	–0.0058	d e
A. implexa	–0.0083	d e
A. glaucocarpa	–0.0084	d e
A. fulva	–0.0090	e
A. decurrens	–0.0095	e f
A. blayana	–0.0104	e f g
A. binervia	–0.0112	e f g
A. parramattensis	–0.0122	e f g
A. dangarensis	–0.0142	e f g
A. parvipinnula	–0.0153	e f g
A. mearnsii	–0.0190	f g
A. irrorata ssp. *irrorata*	–0.0239	g

[1]Species means with the same letter did not differ significantly

Table 6. Percentage heartwood — mean values and the significance of differences based on pairwise t-tests at the 5% significance level, Uriarra

Species	Species means for percentage heartwood	Significance of differences[1]
Acacia dangarensis	43.8	a
A. implexa	42.1	a
A. fulva	34.5	a b
A. glaucocarpa	28.0	b c
A. filicifolia	23.0	c d
A. decurrens	21.2	c d
A. parvipinnula	20.1	c d e
Eucalyptus nitens	19.1	c d e
A. leucoclada ssp. *leucoclada*	18.4	c d e
A. leucoclada ssp. *argentifolia*	18.0	c d e f
A. silvestris	16.8	d e f[2]
A. binervia	13.6	d e f g
A. parramattensis	13.6	d e f g
A. mearnsii	13.2	e f g[3,4]
A. blayana	9.8	e f g
A. dealbata	9.3	f g
A. irrorata ssp. *irrorata*	6.7	g
A. trachyphloia	6.4	g h
A. melanoxylon	2.4	h

[1]Species means with the same letter did not differ significantly
[2]*A. dealbata* and *A. silvestris* were significantly different ($P \approx 0.03$)
[3]*A. mearnsii* and *A. irrorata* ssp. *irrorata* were significantly different ($P \approx 0.01$)
[4]*A. mearnsii* and *A trachyphloia* were significantly different ($P \approx 0.03$)

sampled had a basic density higher than 600 kg m^{-3}. Provenances of *A. fulva* had the highest basic densities (764 kg m^{-3} and 778 kg m^{-3}).

Significance differences ($P < 0.05$) were found among provenances in *A. mearnsii* and *A. silvestris*. Basic density for *A. mearnsii* from Tuross River, NSW (S16621) was 613 kg m^{-3} and differed significantly from the Victorian provenance from Wattle Circle, Omeo Hwy (S17933), which was 726 kg m^{-3}. Similarly the NSW provenances of *A. silvestris* from Deua River (S15852) and Narooma (S16254), with basic densities 602 kg m^{-3} and 621 kg m^{-3} respectively, differed significantly from the Victorian provenance from Bruthen (S17939) at 731 kg m^{-3}.

Trends in basic density with height

There were significant differences ($P < 0.001$) between *Acacia* species in the trend in basic density with tree height (Table 5). Thirteen of the 18 *Acacia* species/subspecies had a mean decrease in density with height as indicated by a negative regression coefficient value for the regression model. Five species had increases in basic density with tree height (*A. dealbata* (+0.0115), *A. trachyphloia* (+0.0101), *A. leucoclada* subsp. *leucoclada* (+0.0080), *A. filicifolia* (+0.0034) and *A. leucoclada* subsp. *argentifolia* (+0.0004). The basic density of *E. nitens* also increased (+0.0200) with tree height.

Variation in percentage heartwood between species

There were highly significant differences ($P < 0.001$) in percentage of heartwood between species and for provenances within species ($P < 0.001$) (Table 6), and some association between density and percentage heartwood at the species level. However, there was no association between percentage heartwood and height, diameter (dbhob), volume and density trend.

The cross-sectional percentage area of heartwood at 20% of tree height, which ranged from 0.9 to 2.2 m, was extremely variable with considerable variation between trees, among provenances and among species. For example, within the 33 trees sampled for *A. mearnsii*, percentage heartwood ranged between 1.7% and 39.0%, and for *A. silvestris* 18 trees varied between 2.1% and 34.4%. The higher-density species such as *A. fulva* (12 trees) varied between 18.4% and 57.2%; *A. dangarensis* (six trees) had a range of 32.7–55.6%, with *A. leucoclada* subsp. *leucoclada* (seven trees) 7.7–23.2%. In lower density species, the heartwood varied between 0% and 22.2% (*A. dealbata*, 10 trees) , and 0.2% and 12.4% (*A. trachyphloia,* seven trees).

In terms of the percentage heartwood at 20% tree height, *A. dangarensis* (43.8%), *A. implexa* (42.1%) and *A. fulva* (34.5%) had the most heartwood and did not differ significantly ($P < 0.05$) from each other. *Acacia melanoxylon* and *A. trachyphloia* had the least heartwood with 2.4% and 6.4% respectively.

Variation in percentage heartwood between provenances

Percentage heartwood at the provenance level ranged from a minimum of 0.0% for *A. melanoxylon* (S18981 Grampians, Vic.)

Table 7. Mean growth and basic density of *A. deanei*, *A. falciformis* and *A. irrorata* subsp. *velutinella*, Uriarra

Acacia species	No. of trees sampled	Dbhob (cm)	Height (m)	Volume (ub) (m^3)	Basic density[1] (kg m^{-3})
A. deanei	2	9.2	8.8	0.027	600
A. falciformis	1	11.2	6.8	0.024	724
A. irrorata ssp. *velutinella*	3	8.7	7.3	0.019	596

[1]Whole-tree, volume-weighted mean basic density

to maximums of 44.1% for *A. implexa* (S18019 Pyalong, Vic.) and 43.8% for *A. dangarensis* (S18608 Mt Dangar, NSW). *Eucalyptus nitens* had 19.1% heartwood on average. There were highly significant differences ($P < 0.001$) in percentage heartwood among provenances within species.

For percentage heartwood, the *A. mearnsii* provenance from NSW (N Bungendore S18975 — 7.6%) differed significantly ($P < 0.05$) from the Blackhill Reserve, Vic. provenance (S18979 — 18.7%) and the Apsley River, Tas. provenance (S15329 — 18.9%). There were no significant differences ($P < 0.05$) between the three *A. silvestris* provenances for percentage heartwood.

Correlations

At Uriarra there was some association between basic density and percentage heartwood at the species level. However, there was no association at the provenance-within-species level. No association was found between species for percentage heartwood and height, dbhob, volume and the trend in basic density with tree height.

Mean growth and basic density of A. deanei, A. falciformis *and* A. irrorata *subsp.* velutinella

Insufficient samples were collected for three *Acacia* species that were consequently excluded from the analyses. However, mean growth and basic density data are given in Table 7 because so little information is available elsewhere on these species.

Kowen

Four provenances sampled at Uriarra were also sampled at Kowen: *A. mearnsii* (S17933 Omeo Hwy, Vic. and S18979 Blackhill Reserve Kyneton, Vic.), *A. decurrens* (S15847 Picton-Mittagong NSW) and *E. nitens* (Badja State Forest, NSW) (Table 1). The 24 trees sampled were unaffected by the cockatoo attacks that damaged the Uriarra trial. Individual tree diameter (dbhob) ranged from 7.4 to 20.2 cm; height from 5.8 to 10.7 m, volume from 0.011 to 0.1 m^3, percentage heartwood from 0.5 to 33.2% and whole-tree, volume-weighted mean basic density from 545 to 711 kg m^{-3}.

Acacia mearnsii (S17933) had the highest mean basic density (688 kg m^{-3}). *Acacia decurrens* had the largest mean percentage heartwood (22.9%) at 20% tree height and *E. nitens* the lowest (2.6%). *Eucalyptus nitens* was the largest species at the Kowen site (9.3 m; 15.3 cm dbhob and 0.069 m^3 in volume under bark) and had the lowest mean basic density (556 kg m^{-3}). There were highly significant differences between the three species for basic density ($P < 0.001$) and percentage heartwood ($P < 0.001$).

Genotype × environment interactions

For basic density the rankings of the predicted values from the regression analysis for the seedlots did not change between Uriarra and Kowen. *Acacia mearnsii* (S17933) had the highest basic density of the four seedlots at both sites, 688 kg m^{-3} at Kowen and 726 kg m^{-3} at Uriarra. *Eucalyptus nitens* had the lowest density (556 kg m^{-3} at Kowen and 530 kg m^{-3} at Uriarra).

Percentage heartwood rankings did change, but amongst the three acacia provenances *A. mearnsii* (S17933) had the lowest percentage heartwood (15.5% at Kowen and 12.3% at Uriarra) at both sites. There was a significant genotype × environment interaction ($P = 0.006$) for percentage heartwood (2.6% at Kowen and 19.1% at Uriarra) in *E. nitens*.

Discussion

The whole-tree, volume-weighted basic density and percentage heartwood data at 8 y of age for 18 *Acacia* species/subspecies add to the scant knowledge of genetic variation in basic density and heartwood in temperate Australian acacias of a known age in Australia. It is difficult to compare these results with other studies because sampling methods have not been standard.

Eight-year-old *A. mearnsii* (33 trees) described in this paper, for example, averaged 663 kg m^{-3} for basic density across six provenances and there was significant variation between the provenances. A New Zealand study (Shelbourne *et al*. 2000) used increment cores taken at 1.4 m from two to four well-grown trees per provenance at each of two sites. The basic density of 35 *A. mearnsii* trees (six Australian provenances), 7 y old, ranged from 521 to 575 kg m^{-3}. Basic wood density did not differ significantly among these provenances or between sites. One of the *A. mearnsii* provenances (Blackhill Reserve, Victoria) in the New Zealand study is an earlier seed collection from the same site as S18979 reported in this paper. The mean basic density of the seedlot planted in New Zealand (six trees across two sites) was 567 kg m^{-3} at 7 y of age. In our study the mean basic density for 12 trees (six at each of two sites) at 8 y was 648 kg m^{-3} but it is not possible to determine if the difference is due to sampling strategy, sampling method, site and/or age differences.

McKinley *et al*. (2000) reported whole-tree, basic wood density aggregated into 5-y age classes for *A. mearnsii* (658 kg m^{-3} for 11 trees at an average age of 14 y) and *A. dealbata* (468 kg m^{-3} for six trees at an average age of 14 y) growing in New Zealand.

Acacia mearnsii trees at Uriarra and Kowen were on average at least 100 kg m^{-3} denser than the two, 6-y-old, effluent-irrigated *A. mearnsii* provenances that Clark (2001) sampled at Bolivar

(South Australia), using a method similar to that used in this study. Again it is difficult to determine the cause of the lower density of *A. mearnsii* in the South Australian trial, which may have been due to the younger age, different genetic origin or the non-limiting supply of water or particular nutrients. However, it is interesting to note that Clark (1999) found that reduced water availability increased the volume-weighted basic wood density in plantation-grown eucalypts, including *E. nitens*. In this study *E. nitens* was denser at the drier site: 556 kg m^{-3} at Kowen compared with 530 kg m^{-3} at Uriarra.

Acacia melanoxylon (blackwood) is a high-value timber species cultivated on a small scale outside Australia. Research in South Africa and New Zealand suggests most heartwood characteristics of *A. melanoxylon* are under combined genetic and environmental control (Searle 2000). Nicholas and Brown (2002) state that the basic density of *A. melanoxylon* in New Zealand plantings is not influenced by growth rate and commented on the 'remarkable variation in [basic] density between blackwood trees of the same age but different genetic origin'. For example, basic density for four provenances ranged between 424 and 498 kg m^{-3} and there were significant differences between provenances ($P < 0.05$). This New Zealand study was based on 59 trees aged 10 y and sampled at a height of 1.4 m. Percentage heartwood of the sampled discs ranged from 42 to 52% (Nicholas *et al.* 1994). In the study reported in this paper, the 8-y-old *A. melanoxylon* trees at 20% tree height had much less heartwood (0.0–19.6%).

Kingston and Risdon (1961) reported that the mean basic density of *A. melanoxylon* of unspecified age (45 trees from natural stands in South Australia, Tasmania and Victoria) was 546 kg m^{-3}. This is within the range of the *A. melanoxylon* reported in this paper, in which basic density of five provenances (from South Australia, Tasmania, Victoria and Queensland) was between 520 and 613 kg m^{-3}.

South Africa's Institute for Commercial Forestry Research planted a small *A. decurrens* progeny test in 2001 and it has been suggested that *A. decurrens* and *A. silvestris* could benefit the country's forestry industry (Dunlop *et al.* 2002) because of their relatively better growth and form than *A. mearnsii*. Major forestry companies in South Africa such as Mondi Forests have conducted wood and pulping quality assessments of *A. decurrens* as the first step in a breeding program. In our study, *A. decurrens* (two provenances) had a whole-tree, volume-weighted mean basic density of 647 kg m^{-3} and *A. silvestris* (three provenances) had a mean basic density of 654 kg m^{-3}. These figures suggest that these species would be comparable in basic density to the widely-planted *A. mearnsii*.

In this study, three acacias, *A. trachyphloia* (568 kg m^{-3}), *A. dealbata* (570 kg m^{-3}) and *A. melanoxylon* (576 kg m^{-3}), were similar in basic density to the commercially-planted *E. nitens* (530 kg m^{-3}). The other 15 *Acacia* species/subspecies were significantly denser than the fast-growing eucalypt.

Of particular note are the lesser-known, rare, bipinnate species such as *A. dangarensis*, *A. fulva* and *A. leucoclada* subsp. *leucoclada* and *A. leucoclada* subsp. *argentifolia* that are closely related to *A. mearnsii* (mean basic density 663 kg m^{-3}) but had the highest densities (719–771 kg m^{-3}) amongst the 18 *Acacia* species. These are worthy of further investigation for short rotation (≤ 10 y) products requiring relatively greater density and more heartwood.

There was no genotype × environment interaction for basic density or percentage heartwood between the three acacia seedlots (*A. mearnsii* — two provenances and *A. decurrens* — one provenance) sampled from two sites. This suggests that either the two sites were not distinctly different from each other or the two species are relatively stable over the planting sites.

Basic density is a critical determinant of a species' suitability and profitability for particular wood products (Maslin and McDonald 2004). If basic density in temperate acacias is under strong genetic control as it is in eucalypts (Raymond 1995), it will be possible to use the significant variation between and within species to select the most suitable genotypes for breeding for increased uniformity in the desirable basic wood density characteristics for specific wood uses. For kraft pulpwood in particular, Greaves and Borralho (1996) concluded that density has greater exploitable genetic variation than pulp yield, and therefore may be more important in breeding.

Conclusions

Whole-tree, volume-weighted mean basic wood densities for 18 tree-form temperate *Acacia* species/subspecies (40 provenances) were between 568 and 771 kg m^{-3} and provenance means ranged between 520–778 kg m^{-3}. Results from this study highlight the ability of many temperate *Acacia* species to produce relatively dense wood in only 8 y. There was highly significant ($P < 0.001$) variation in basic density between the *Acacia* species sampled for this study.

Percentage heartwood sampled at 20% of tree height was highly variable and means were in the range 2.4–43.8% for species and 0.0–44.1% for provenances. There were highly significant differences between the *Acacia* species for percentage heartwood ($P < 0.001$). There was some association between percentage heartwood and basic density at the species level but no association at the provenance within species level.

There were highly significant differences between acacia species in the trend in basic density with tree height.

Provenance variation in *Acacia mearnsii* in basic density and percentage heartwood, and in *A. silvestris* for basic density was significant ($P < 0.05$) and could be exploited in breeding programs.

Analysis to investigate geographic patterns in the observed phenotypic traits for provenances within wide-ranging species such as *A. mearnsii* will be the subject of another paper.

For temperate Australian *Acacia* species with commercial potential, further research is required to adequately describe and understand the pattern of variation in basic density with genotype, age, management and site conditions. It is also essential to develop non-destructive sampling strategies for accurate whole-tree predictions of basic density once the pattern of variation within and between trees has been determined.

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