Review of growth and wood quality of plantation-grown *Eucalyptus dunnii* Maiden

Dane Thomas[1,3], Michael Henson[1], Bill Joe[2], Steve Boyton[1] and Ross Dickson[2]

[1]Forests NSW, Land Management and Forestry Services, PO Box J19, Coffs Harbour, NSW 2450, Australia
[2]Forests NSW, Land Management and Forestry Services, PO Box 100, Beecroft, NSW 2119, Australia
[3]Email: danet@sf.nsw.gov.au

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Summary

Forests NSW manages *Eucalyptus* plantations on the north coast of NSW, Australia, for high-value timber production. One species increasingly being planted both in Australia and overseas is *Eucalyptus dunnii* Maiden. For a species to be considered suitable for forestry, criteria to be met include successful establishment, growth and suitability for end use, be that pulp, solid wood or veneer production.

Historic data from *E. dunnii* plantations aged from 3 to 34 y were reviewed. Growth and wood quality using a range of non-destructive and destructive measurements are reported. *Eucalyptus dunnii* typically grew equally well as some alternative species, although species ranking was affected by the growing site. *Eucalyptus dunnii* produced high-quality wood chips with average pulp yield from three NSW plantations aged 8–10 y of 53% and 265 kg m^{-3}. This yield is comparable with that of 10-y-old *E. globulus* plantation material from Tasmania. Wood density increased with tree age from about 500 kg m^{-3} at age 10 y to 600 kg m^{-3} at age 25 y, and more slowly beyond that age. Many solid-wood quality traits such as hardness and strength could be positively correlated with both tree age and basic density. This has implications for the timber industry as it is intended that plantation trees will be harvested at younger ages than native forest trees, but wood quality in such younger material may not satisfy minimum product performance requirements. However, trees selected for higher density achieved strength group ratings at age 9 y that would normally be achieved at age 25–30 y. It is not known if similar improvements can be made in other wood quality traits. Quality traits requiring further examination are growth stresses and endsplitting of logs, and shrinkage of sawn timber. Collapse (reversible shrinkage) and non-reversible shrinkage are positively related to wood density, but a greater concern is the high ratio of tangential shrinkage compared to radial shrinkage. This ratio, which can be 2.5 or greater in *E. dunnii*, leads to excessive distortion in sawn material. It may be possible to reduce overall wood shrinkage and the ratio of tangential to radial shrinkage, as well as other unfavourable wood quality traits, through genetic selection as these traits in related eucalypts (e.g. blackbutt, *E. pilularis*) are heritable.

Keywords: plantations; growth rate; wood properties; pulpwood; yields; wood density; growth stress; modulus of elasticity; hardness; shrinkage; genetic improvement; Dunn's white gum; *Eucalyptus dunnii*

Introduction

Eucalyptus dunnii Maiden (Dunn's white gum) naturally occurs in two small disjunct populations on north-eastern New South Wales (NSW) and south-eastern Queensland, Australia, primarily on the margins of rainforests (Boland *et al*. 2006). These sites, at between 400 m and 650 m altitude, have a mean annual rainfall of 1100–1500 mm with a summer maximum, and typically fertile basaltic or alluvial soils (Benson and Hager 1993). *Eucalyptus dunnii* has recently gained favour as an alternative plantation species to *E. grandis* because it is better suited to drier and or more frost-prone sites (Darrow 1994; Johnson and Arnold 2000). This has lead to its establishment mostly on higher-altitude sites (>500 m asl), or on lower-lying creek flats prone to frost. In NSW, Forests NSW (FNSW) has established over 8500 ha, mostly since 1994. This review uses available data from Australian and international research to report on growth of plantation-grown *E. dunnii*, and the suitability of the plantation-grown wood for a variety of end uses. Wood properties of plantation-grown *E. dunnii* of different ages and of mature *E. dunnii* from the native forest resource are reported to illustrate the development of wood characteristics with tree maturity, and to identify differences between material from plantations and native forests. We have included all available data in the figures presented to display relationships and to compare the characteristics of wood from Australian plantations of *E. dunnii* with those of wood grown elsewhere, but have used only data from NSW (or Queensland if that was available) plantations for regressions.

Growth

Several trials from NSW were available to examine growth of *E. dunnii* including species trials established between 1972 and 1976 on a range of soil types, climate and local within-site environments that are useful to compare the performance of *E. dunnii* with alternative forestry species such as *E. pilularis* and *E. grandis* (Johnson and Stanton 1993). These trials were planted at 1111 stems ha^{-1} (sph) (3 m espacements between and within rows) and were not thinned during the rotation. The trial sites include:

- Bulahdelah State Forest (SF) (latitude 32°24′S, longitude 152°15′E), sandstone or mudstone, mean annual rainfall (MAR) 1360 mm, altitude 60 m
- Cascade SF (30°13′S, 152°46′E), siliceous argillates and slates, MAR 1280 mm, altitude 640 m
- Chichester SF (32°14′S, 151°46′E) carboniferous sediments, MAR 1550 mm, altitude 800 m
- Yabbra SF (28°32′S, 152°34′E), siltstone or sandstone, MAR 1080 mm, altitude 520 m.

Figure 1 shows diameter over bark at 1.3 m (dbhob) and tree height of *E. dunnii*, *E. grandis* and *E. pilularis* grown in these species trials at ages between 14 and 18 y (typically when the last age measurements were taken) (Johnson and Stanton 1993). The data show growth was comparable between the three species within a site, signifying that *E. dunnii* performs as well as an alternative species, although site effects existed for all species.

Figure 1 shows growth of *E. dunnii* at two of these species trials, at Cascade SF and Chichester SF, in greater detail as these sites have been used for wood quality assessments. Figure 1 also shows growth over time for two FNSW *E. dunnii* progeny trials planted in 1995 at:

- Boambee SF (30°18′S, 153°03′E), yellow podzolic soils, MAR 1700 mm, altitude 60 m
- Megan SF (30°17′S, 152°47′E), yellow podzolic soils, MAR 1600 mm, altitude of 730 m.

The Boambee SF and Megan SF progeny trials were planted at 1388 sph on rows 3 m apart and 2.4 m apart within the rows. Both trials were thinned from 1388 sph to 694 at age 4.5 y. The Boambee SF progeny trial was thinned to 347 sph in late 2007. These data show growth at the two progeny trials was similar to that at the earlier-planted species trials, although site effects are noticeable. Boambee SF is a higher-quality site with predicted MAI at 20 y of 20 m^3 ha^{-1} compared to 15 m^3 ha^{-1} at Megan SF (Henson and Vanclay 2004). Growth of 9- and 14-y-old *E. dunnii* in Argentina was comparable to these reported values (Marco and Lopez 1995), but diameter growth of *E. dunnii* in Brazil aged 8–19 y was almost double that observed in NSW, although height growth was similar (Trugilho *et al.* 2005).

Although the growth of *E. dunnii* in NSW plantations — measured as diameter, height or volume — is similar to that of other better-known species such as *E. pilularis* and *E. grandis*, 'growth' is only one attribute of a species grown for timber. The end use of the timber also has to be considered. A study is in progress to examine potential end uses of *E. dunnii* from plantations of various ages — the Boambee SF trial was harvested in 2007 at age 12 y, and the properties of solid wood, veneer and pulp wood from this high-performing young stand are being assessed; two other sites aged 17 y (Newry SF) and 34 y (Cascade SF) were also harvested in 2007 and similar end uses evaluated. Records of destructive and non-destructive assessments of growth and wood quality traits relevant to pulping and solid-wood products are available for these three sites.

Density

Wood is often characterised by density because this property is correlated, although perhaps not always causally related, with many other quality traits. Denser wood tends to be stronger, but may have greater shrinkage and more checks when dried. Denser wood contains more wood per unit volume and tends to give a higher yield of pulp in paper manufacturing. Thus information about wood density is useful to plantation management.

Overall wood density typically increases with tree age as the proportion of lower-density material formed early in a tree's life is reduced by the formation of higher-density material in older trees (e.g. de Silva *et al.* 2004). Basic density of native forest

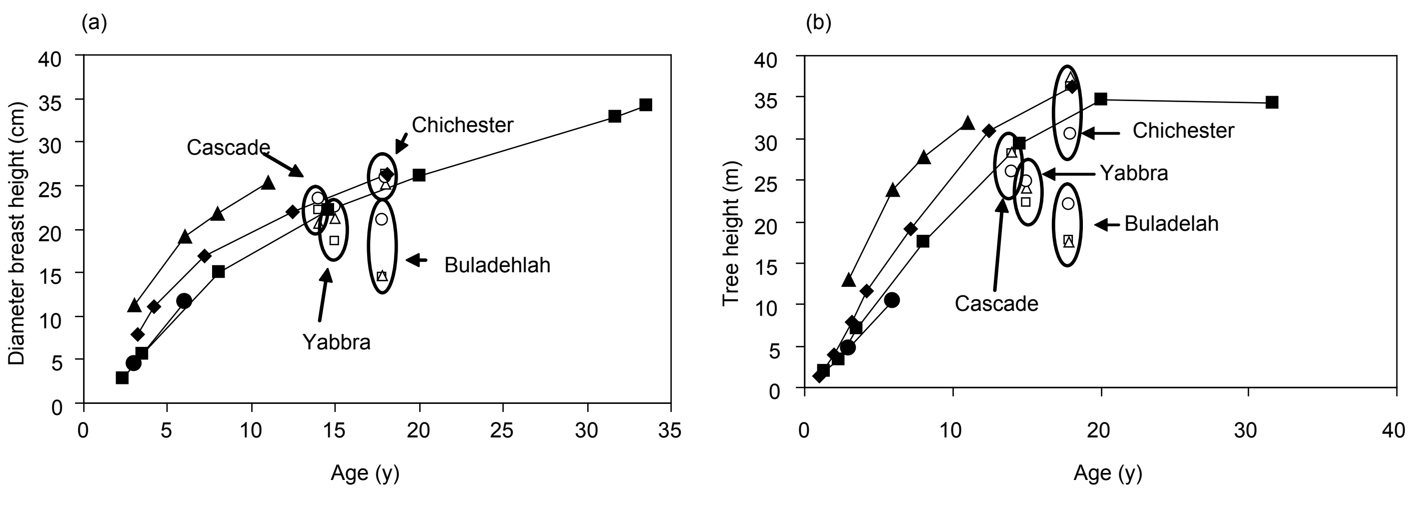

Figure 1. Mean diameter over bark at 1.3 m (a), and mean tree height (b) at last formal measurement of *E. dunnii* (open square), *E. grandis* (open triangle) and *E. pilularis* (open circle) from four trials. The measurements of the four trials are encircled. Mean tree growth of *E. dunnii* over time for two of these trials at Cascade (solid square) and Chichester (solid diamond) is shown. Mean growth at two *E. dunnii* progeny trials at Boambee SF (solid triangle) and Megan SF (solid circle) is shown.

E. dunnii is reported to be 610 kg m^{-3} (Bootle 2005). These data would have been based on tests of wood from mature stands. Data on basic density from 12-mm diametric (bark-to-bark) cores and whole disks at breast height (1.3 m), and estimates of whole-tree density, were used to develop a relationship with tree age for material grown in NSW plantations. Data on plantation-grown material from NSW and elsewhere shows a trend of increasing basic density in older trees to about 600 kg m^{-3} at 25 y, although there is some variability with method of sampling and or site with non-NSW sites (predominantly South American) (Ribeiro and Filho 1993; Marco and Lopez 1995; Calori and Kikuti 1997; Ferreira *et al*. 1997; Backman and deLeon 1998; Dickson *et al.* 2003; Arnold *et al*. 2004; Henson *et al*. 2004; Trugilho *et al.* 2005; Muneri *et al.* 2007) (Fig. 2). The (log transformed) density of Australian plantation-grown *E. dunnii* was highly correlated with tree age, with a coefficient of determination (R^2) of 0.85, n = 17.

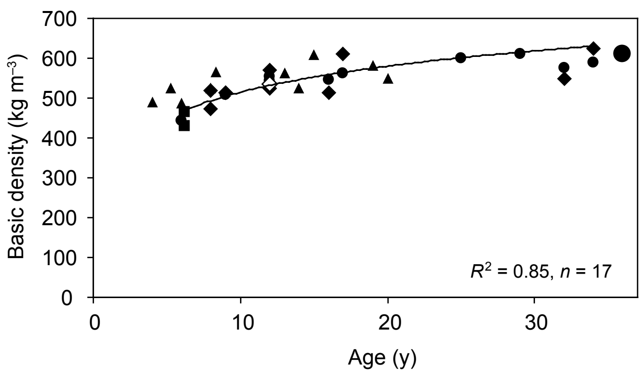

Figure 2. Basic density of *E. dunnii* as a function of tree age. NSW plantation data were estimated from whole trees (solid diamond), calculated from disks (small solid circle), or wood cores (solid square). Data from one Queensland plantation using whole-tree data are shown (open diamond). The logarithmic regression with a coefficient of determination of 0.85 was calculated with data from 16 NSW plantations and one Queensland plantation where density was derived from wood samples and not Pilodyn needle penetration. Data from overseas plantations are shown (solid triangle). Density of mature trees from native forest is shown as a large solid circle plotted as an age of 36 y for the purpose of graphic display, but was not used in the regression.

Pulp characteristics

Site and age can affect pulp yield and quality. Pulp characteristics of *E. dunnii* from a number of sites have been evaluated (Table 1). *Eucalyptus dunnii* from 8-y-old trees grown at Boambee SF were easier to pulp, produced 53% screened pulp and had a higher pulp yield of 277 kg m^{-3} compared to trees of the same age grown at Megan SF which produced 50% screened pulp and a pulp yield of 237 kg m^{-3} (Muneri *et al*. 2007). Trees at Boambee SF were also about twice the height and diameter and four times the volume of trees at Megan SF (Fig. 1). The pulping results at Boambee SF are similar to both 9-y-old *E. dunnii* grown at Newry SF in northern NSW and 12-y-old material from Gympie, Queensland (Hicks and Clark 2001); and to *E. dunnii* aged 9 y in South Africa (Swain *et al*. 2000) and 4 y in Uruguay (Backman and deLeon 1998). The screened pulp yield of 55% for the 9-y-old Newry site was higher than 10-y-old *E. globulus* from Tasmania (Hicks and Clark 2001). Furthermore Hicks and Clark (2001) rated *E. dunnii* from Newry amongst the top three of 23 combinations of species and sites for value as woodchips based on bulk densities, alkali requirements and pulp yields, and over 10% better than Tasmanian export woodchips from native forests.

Site also affected pulp quality, the average fibre length being longer, 0.86 mm, at Boambee SF than the 0.74 mm at Megan SF, the latter being similar to results reported from South Africa (Muneri *et al.* 2007). This is important as fibre length can affect paper quality (Wimmer *et al.* 2002). Silvicultural practices such as stocking can also affect pulp productivity of *E. dunnii* (Ferreira *et al.* 1997) through, amongst other factors, changes in pulping characteristics, tree diameter and height growth, and wood density.

Pulp yield of 8-y-old *E. dunnii* growing at Boambee SF and Megan SF plantations was recently estimated using near-infrared spectroscopy (Muneri *et al.* 2005). This technique offers fast, cost-effective evaluation of the economic potential of trees. The predicted values were within 2% of observed values, with high correlation coefficients. It is recommended that this technique be tested on other sites and older trees to determine its wider application.

Table 1. Pulping characteristics of plantation-grown *Eucalyptus dunnii*, with 10-y-old plantation-grown *E. globulus* from Tasmania as a comparison

Plantation location	Age (y)	Active alkali (% Na_2O)	Pulp yield (%)	Yield (kg m^{-3})	Reference
Boambee SF, NSW	8	12.8	53.3	277	Muneri *et al.* 2007
Megan SF, NSW	8	13.8	50.1	237	Muneri *et al.* 2007
Newry SF, NSW	9	12.3	54.8	282	Hicks and Clark 2001
Gympie, Qld	12	13.9	51.6	276	Hicks and Clark 2001
South Africa	9	NA	50.3	256	Swain *et al.* 2000
Uruguay	4	14.6	50.1	245	Backman and deLeon 1998
Tasmania, *E. globulus*	10	11.5	53.8	268	Hicks and Clark 2001

NA denotes data not available

Solid wood

Growth stresses

Solid-wood properties of *E. dunnii* are in many ways more difficult to ascertain than density or pulping characteristics. A common problem of plantation-grown wood as opposed to native forest material is related to growth stresses. It is generally accepted among researchers that growth stresses are generated in the secondary xylem during cell maturation (Jacobs 1938; Kubler 1987). However, theories put forward to explain the generation mechanism remain controversial and unresolved. Two theories that have survived to the present day are the 'lignin swelling' theory advanced by Boyd (1972, 1985) and the 'cellulose tension' theory advanced by Bamber (1979, 1987). Neither theory appears to apply in all circumstances. More recently, Yamamoto (1998) introduced a unified hypothesis that incorporated both lignin swelling and cellulose tensioning, and implicated microfibril angle (MFA), in generating growth stresses. The lignin swelling hypothesis became relevant in the region of the cell wall with a large MFA (i.e. compression wood fibre), whilst the cellulose tension hypothesis became relevant in the region of the cell wall with a small MFA (i.e. normal and tension wood fibre).

Regardless of the mechanism of generation, the occurrence of growth stresses is not in doubt and is thought to be related to the growth rate of trees; the stresses or stress gradients often decline with tree age. Excessive growth stresses can result in endsplitting of logs after they are felled and considerable downgrading of log quality. Growth stress manifested in the form of endsplitting is under genetic control in *E. dunnii* (Anonymous 1999; Swain *et al*. 2000), which suggests the possibility of using genetic selection to reduce losses from endsplitting. Silvicultural management may also affect growth strains and hence endsplitting. Peripheral growth strains in 9-y-old *E. dunnii* grown at Boambee SF were evaluated by Murphy *et al.* (2005). Growth strain was found to be heritable, but it was also observed that taller thinner trees had higher growth strain than short thick trees (Murphy *et al.* 2005), suggesting strain may be altered by site and the influences of silvicultural practices on stem taper.

Growth stresses are also a major concern when processing timber. It has been estimated that one-third of material sawn from plantation-grown *E. dunnii* may suffer degrade attributable to growth stress (Matos *et al*. 2003). Similar degrade was reported in 10-y-old plantation-grown *E. globulus*, where 30% of boards were rejected due to excessive distortion and 40% of this distortion could be attributed to growth stress (Yang *et al.* 2001, 2002). It is therefore not surprising that methods have been examined to reduce losses due to growth stress. Alternative sawing techniques are available which rely on removing stresses over the entire log, which increases timber recovery. These techniques have allowed the successful production of structural timber from young plantation-grown material of several eucalypts. Additionally various methods have been used to reduce and release growth stresses prior to harvest (Malan 1995). Techniques such as girdling of standing trees, or partial defoliation prior to harvest, were shown to reduce growth stresses of *E. grandis* although variation between trees and decay of girdled trees was excessive (Malan 1995). Herbicide and radial cuts were most effective in reducing growth stresses of *E. dunnii* (Matos *et al.* 2003). Post-harvest steaming treatments prior to milling were also effective in reducing splitting and other growth-stress-related defects in *E. dunnii* (Severo and Tomaselli 2000).

Mechanical properties

Modulus of elasticity (MOE) and modulus of rupture (MOR) are the principal mechanical properties dictating uses of solid wood.

Modulus of elasticity

Modulus of elasticity is a measure of stiffness of wood and has traditionally been determined by static bending of standard clearwood specimens. It is less of a problem with hardwoods than softwoods, although juvenile wood from plantation-grown trees of both may have unacceptable MOE. Static bending MOE in *E. dunnii* increased with wood density in five NSW plantations, but the relationship with tree age was weaker (Fig. 3). Data from Brazil also show that MOE (measured in tension) increased with tree age and or wood density (Fig. 3) (Trugilho *et al.* 2005). However, wood from these Brazilian plantations had much higher MOE than that from NSW plantations.

MOE increases over time, although neither tree age nor basic density was a wholly satisfactory explanatory variable. MOE is influenced by density and microfibril angle, with that angle accounting for more variation than density (Evans and Ilic 2001; Yang and Evans 2003). In combination, density and microfibril angle can account for over 90% of MOE in plantation eucalypts (Evans and Ilic 2001; Yang and Evans 2003). The relationship between MOE and density (Fig. 3a) shows MOE of wood from mature *E. dunnii* was higher than predicted using data from plantation-grown *E. dunnii* despite having similar basic density. As microfibril angle typically declines with tree age (e.g. Lindströ̋m *et al.* 1998; Evans *et al.* 1999), and as large gains in MOE are realised with relatively small changes in microfibril angle (e.g. Yang and Evans 2003), it seems likely that the MOE of mature native forest material is more influenced by lower microfibril angle than younger plantation material, despite having similar basic density.

MOE can also be predicted from acoustic measurements such as the FAKOPP microsecond timer. Of three acoustic instruments tested, Henson *et al.* (2004) found the FAKOPP microsecond timer gave the most accurate predictions of MOE. MOE of older *E. dunnii* plantations predicted using a linear relationship between MOE and the FAKOPP readings showed MOE to be greater than 14 GPa in stands aged 12 y or older. This MOE is similar to that predicted from the relationship between age and MOE (Fig. 3b).

Management of stem taper may also affect strength of processed timber as stem taper has also been related, albeit weakly, to strength of loblolly pine (*Pinus taeda* L.) solid wood and veneer (Floyd *et al*. 2006). It has yet to be determined if similar relationships exist in eucalypts.

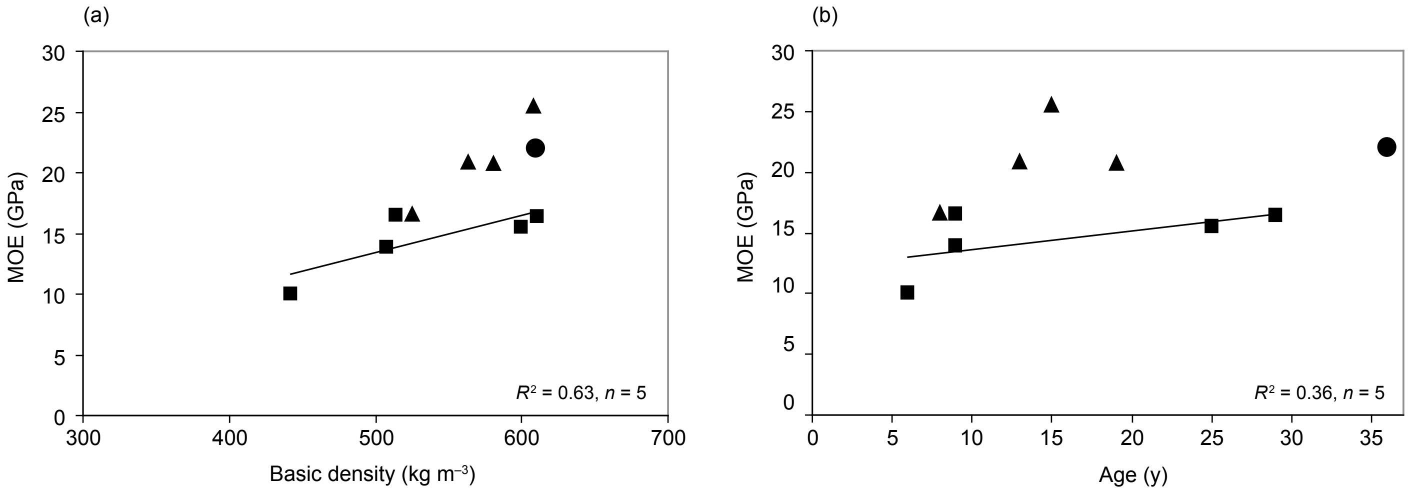

Figure 3. Modulus of elasticity (MOE) of static bending as a function of basic density (a), and of age (b) of *E. dunnii*. Material from NSW plantations (solid square) was used for the linear regressions which had coefficients of determination of 0.63 and 0.36 for the relationship with basic density and with age respectively. Data from mature trees in native forest are shown as a large solid circle and plotted as an age of 36 y for the purpose of graphic display, but were not used in the regressions. MOE in tension values of Brazilian material are also included (solid triangle).

Modulus of rupture

Modulus of rupture (MOR) was found to be related to density and to age in plantation-grown *E. dunnii* (Fig. 4). Both correlations were highly positive, with a coefficient of determination of 0.91 for the relationship with basic density and 0.67 for the relationship with tree age. The MOR data for *E. dunnii* from mature native forest (Bootle 2005) were comparable to the experimental data for plantation wood of similar density (Fig. 4a).

Strength group (SD)

MOR and MOE are the key determinants of quality of solid-wood products used in structural applications (e.g. floor joists, lintels, trusses, girders). Under the Australian strength classification system using AS/NZS2878:2000 (Standards Australia 2000), species are classified into 'strength groups' based on minimum mean MOR and MOE values. Individual sawn boards are then assigned stress grades (F-grades) depending on the size and type of defects present. For seasoned timber, there are eight strength groups from SD1 to SD8 in descending order of strength. Figure 5 shows the strength grouping of plantation-grown *E. dunnii* improving with age. This is an important relationship as it indicates that the utilisation potential improves with plantation age. The predictive equation indicates that a tree age of 22 y is necessary before SD4 is attained, and 30 y for SD3; the latter corresponds to stress grades from F14 to F27 depending the extent of strength-reducing characteristics present in the boards. Material selected from a progeny trial at age 9 y for high density had a

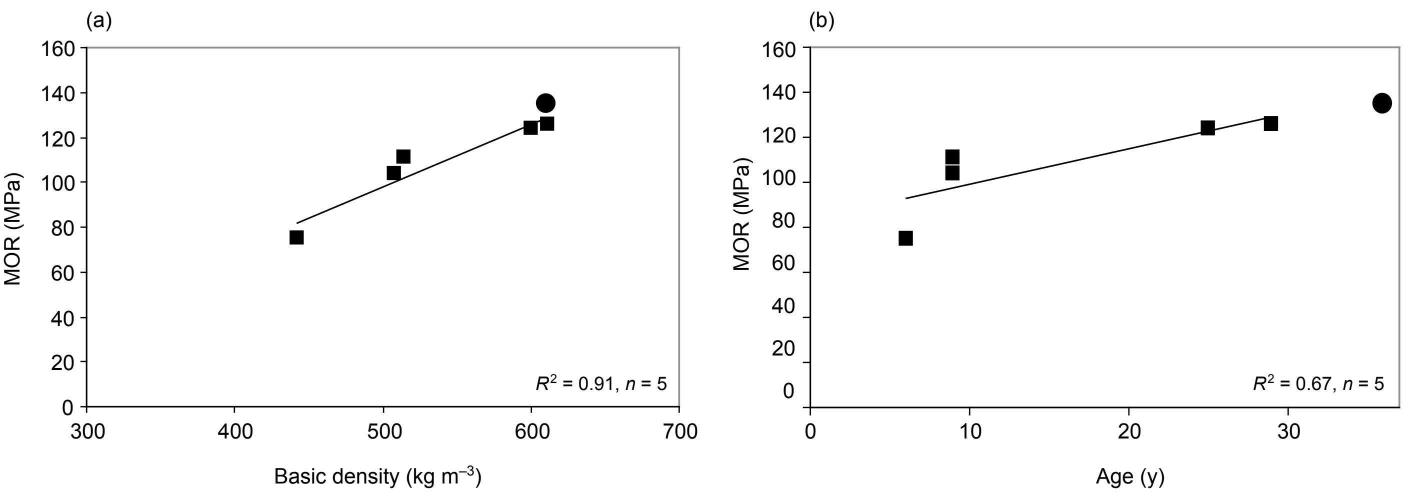

Figure 4. Modulus of rupture (MOR) of *E. dunnii* as a function of basic density (a) and of age (b) of NSW plantation material (solid square), and the regressions calculated using these data. Material from NSW plantations (solid square) was used for the linear regressions which had coefficients of determination of 0.91 and 0.67 for the relationship of MOR with basic density and with age respectively. Data from mature trees in native forest are shown as a large solid circle plotted as an age of 36 y for the purpose of graphic display, but were not used in the regressions.

superior strength group (i.e. SD3) than the general relationship with plantation age would suggest (i.e. SD5, which corresponds to stress grades F8 to F17). The general relationship predicts trees would be 20 y older before a similar SD rating was achieved in unselected material. It would be assumed that this selected material would maintain its overall stronger SD rating as it continues to grow, and that newly established plantations using genetically improved material could produce better timber at a younger plantation age.

Hardness

Wood hardness is a measure of resistance to indentation, and provides an indication to how well the wood in service performs in relation to wear and marking. It is an important quality trait for flooring and furniture, but less important for other solid-wood products. The Janka method (Mack 1979) was used to determine the hardness values reported here. Phenotypic correlations between hardness and density of eucalypts including *E. dunnii* have been shown to be positive (e.g. Dickson *et al.* 2003). The regressions of hardness and density, and hardness and tree age, using NSW plantation-grown *E. dunnii* were positive and highly correlated (Fig. 6). Data from mature *E. dunnii* and *E. dunnii* grown in Brazil agree with these relationships, suggesting hardness will increase with plantation age because density will increase with plantation age.

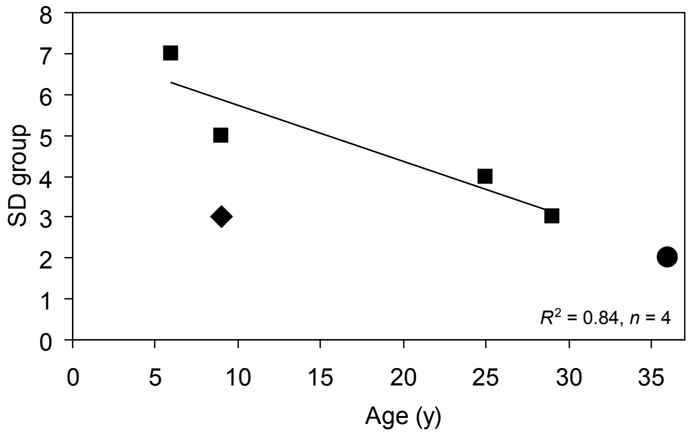

Figure 5. Seasoned strength (SD) group as a function of age for *E. dunnii* grown in NSW plantations (solid square) and of 9-y-old material selected for high density (solid diamond). Only the four data points of non-selected material were used to develop the linear regression which had a coefficient of determination of 0.84. Data from mature trees in native forest are shown as a large solid circle plotted as an age of 36 y for the purpose of graphic display, but were not used in the regression. (Strength is inversely related to the group category number.)

Shrinkage and collapse

It is generally accepted that denser woods will shrink (and swell) more than lower-density woods as they have proportionately more cell wall and less lumen (e.g. Kollman and Côté 1977; West 2006). The cell wall of denser wood contains larger amounts of water such that as water is removed from the cell wall during drying, the volume of cell wall decreases (i.e. shrinks) by an equivalent amount. The relationship between basic density and shrinkage after reconditioning to overcome collapse or reversible shrinkage during drying for NSW plantation-grown *E. dunnii* was positive (Fig. 7). The corresponding values for wood from mature trees provided by Bootle (2005) generally agree with those for plantation-grown *E. dunnii*. Recoverable shrinkage (collapse) accounted for about 4% tangentially and 1% radially in this NSW plantation material irrespective of density (or age), which meant that the relationship between density and shrinkage was not affected.

Bootle (2005) lists tangential shrinkage of mature native forest *E. dunnii* of an unknown age to be 10% and radial shrinkage at 5%, giving a ratio between tangential and radial shrinkage of 2.0. Lower shrinkage ratios are desirable as cupping of boards during drying would be reduced with more uniform shrinkage. Older plantation-grown *E. dunnii* has shrinkage comparable to that of the mature trees whose properties are given in Bootle (2005) (Fig. 8).

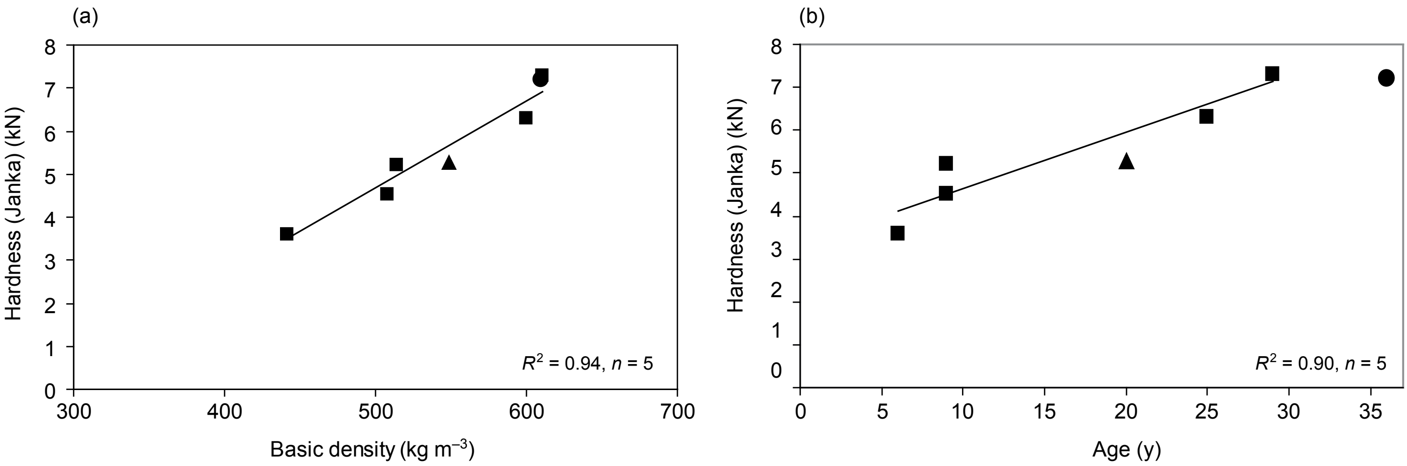

Figure 6. Hardness of *E. dunnii* as a function of basic density (a) and of age (b) for NSW plantation material (solid square) and non-NSW data (solid triangle). The linear regressions were calculated using plantation-grown material from NSW. These regressions had coefficients of determination of 0.94 and 0.90 for the relationship of hardness with basic density and with age respectively. Data from mature trees in native forest are shown as a solid circle plotted as an age of 36 y for the purpose of graphic display, but were not used in the regressions.

Tangential shrinkage of 10.2% and radial shrinkage of 6.2% were found in 20-y-old Brazilian plantation *E. dunnii*, giving a lower ratio between tangential shrinkage and radial shrinkage of almost 1.5 (Calori and Kikuti 1997). Shrinkage after reconditioning to recover collapse of 29-y-old *E. dunnii* at Chichester, NSW, was 8.4% tangentially and 3.2% radially (Joe, FNSW, unpublished data), while shrinkage after reconditioning to recover collapse of 6-y-old *E. dunnii* was 6.2% tangentially and 2.2% radially (Joe, FNSW, unpublished data). These shrinkage values are less than those for the Brazilian trees, but in each case the ratio between tangential and radial shrinkage was higher at 2.6 for the 29-y-old material and 2.8 for the 6-y-old material. Recoverable collapse in the NSW plantation material accounted for about 4% of tangential shrinkage but less than 1% of the radial shrinkage (Joe, FNSW, unpublished data). Recovery of this collapse could lead to checking and be detrimental to appearance-grade products (Harwood *et al.* 2005).

Shrinkage in 6- and 9-y-old plantation-grown *E. dunnii* from NSW has also been examined on 12-mm diametric (bark-to-bark) pseudo-cores (Arnold *et al*. 2004; Bandara 2006; Johnson FNSW, unpublished report). Total tangential shrinkage before reconditioning of the 9-y-old material was 17.4% — tangential shrinkage measured after reconditioning was 7.1% while collapse was found to be 10% (Bandara 2006). No data were available of radial variation in these shrinkage or collapse values. However, Henson *et al*. (2004) reported tangential and radial shrinkage of boards — obtained from this material and dried quickly to

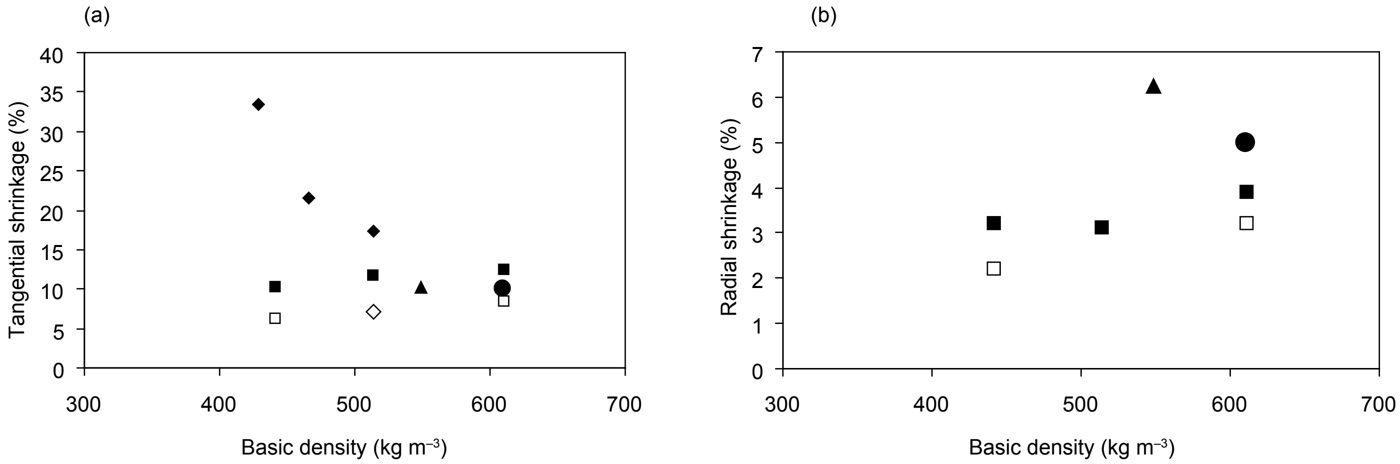

Figure 7. Tangential (a) and radial (b) shrinkage before and after reconditioning of plantation-grown *E. dunnii* as a function of basic density. Shrinkage was measured on blocks or boards before reconditioning (solid square) and after reconditioning (open square); or on 12-mm diametric cores before reconditioning (solid diamond) and after reconditioning (open diamond). Non-NSW data are shown as solid triangle and it is unknown if this is before or after reconditioning. Data from mature trees in native forest are shown as a large solid circle.

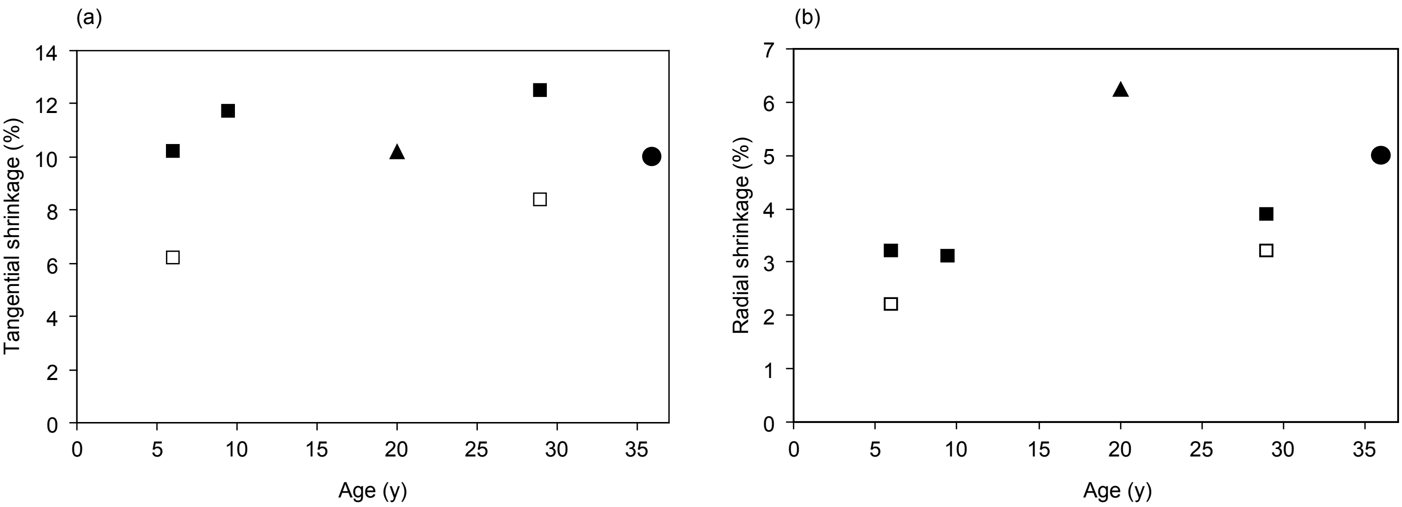

Figure 8. Tangential (a) and radial (b) shrinkage before and after reconditioning of plantation-grown *E. dunnii* as a function of age. Shrinkage was measured on blocks or boards before reconditioning (solid square) or after reconditioning (open square). Non-NSW data are shown as solid triangles and it is unknown if this is before or after reconditioning. Data from mature trees in native forest are shown as a large solid circle, and plotted as an age of 36 y for the purpose of graphic display.

exacerbate distortion — to be 11.7% and 3.1% respectively. This corresponds to a ratio of tangential to radial shrinkage of 3.8, a value higher than in other reports.

The high ratio of tangential to radial shrinkage in wood from NSW plantations is of concern as sawn material will be under differential stresses while drying, which may lead to drying-related defects such as cupping (Harwood *et al.* 2005). Harwood *et al.* (2005) and Bandara (2006) noted that a high percentage of boards sawn from 9-y-old material displayed cupping after drying. Following reconditioning, 27% of these boards had unrecoverable collapse-related defects on an average of 60% of their length, while surface checking was visible on less than 0.1% of the board length (Harwood *et al.* 2005; Bandara 2006).

It is interesting to note that the higher ratio of tangential to radial shrinkage in material from NSW plantations is different to that in material from both the older native forest resource and the 20-y-old plantations in Brazil. This suggests this difference is not solely related to age of the material. The higher ratio in the NSW plantation material was due more to proportionally much lower radial shrinkage in the NSW plantation material than to differences in tangential shrinkage between the trees from the three sources. Why NSW plantation material would have less radial shrinkage is unclear. Differential transverse shrinkage can be due to many factors including gross anatomical structures such as cell lumen size or cell wall thickness, or the presence of wood rays, or more detailed structure such as cell wall microfibril angle, or composition of the middle lamella (Kollman and Côté 1977). Clearly the higher ratio of tangential shrinkage to radial shrinkage of NSW plantation-grown *E. dunnii* needs to be addressed. Gains could be made through greater use of improved genetic material as it has been shown that wood traits are highly heritable, and that in *E. pilularis* tangential and radial shrinkage and their ratio is under genetic control (Pelletier 2006; Raymond *et al*. 2007).

Shrinkage of wood is a further quality attribute that is correlated with both growth stress and density. Ten-year-old *E. nitens* with low growth stress had less shrinkage (Chauhan and Walker 2004), while Yang *et al*. (2002) found a weak negative relationship between tangential shrinkage and growth stress of 10-y-old *E. globulus*. A strong positive relationship existed between growth stress and the difference in shrinkage between heartwood and sapwood of *E. nitens* (Chauhan and Walker 2004). Shrinkage of *E. globulus* sapwood was typically low, being about half that of outer heartwood (Yang and Pongracic 2004). These shrinkage results may in part be due to differences in density or extractives content (which act as a bulking agent) between the outer heartwood and sapwood. It is clear the relationship between growth stress and shrinkage requires further research.

Conclusion

Wood from *E. dunnii* plantations shows increasing basic density as stands age. Basic density was correlated, although perhaps not causally related, with many other wood quality traits. These traits, including shrinkage and structural characteristics such as hardness, MOE and MOR, showed linear increases with both basic density and stand age. The increasing MOR and MOE corresponded to increased strength and improved strength group (SD grade), highlighting the higher quality of denser material from older stands. As these traits, along with growth characteristics such as tree volume and diameter, heavily influence end product recovery and value, it should be realised that plantation-grown material which is usually harvested at younger ages than trees in native forest material may be of different quality.

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