Variation in Wood Properties of Plantation-Grown *Eucalyptus dunnii* relevant to Solid-Wood Products
Publication: Variation in Wood Properties of Plantation-Grown Eucalyptus dunnii relevant to Solid-wood products

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*Eucalyptus dunnii* Relevant to Solid-Wood Products

Prepared for the 
Forest & Wood Products 
Research & Development Corporation

by 

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EXECUTIVE SUMMARY

Objectives

This study aimed to:

- Evaluated possible low-cost methods of assessing solid-wood value of plantation-grown *E. dunnii* trees using the tangential shrinkage properties of fixed-height increment cores.
- Relate wood microstructure to core shrinkage properties.
- Yield information on potential kiln-drying regimes that would enable genetic differences in processing performance to be determined.
- Assess the quality of kiln-dried, sawn boards from plantation-grown *E. dunnii*.

Key Results

Core samples 12 mm in diameter were taken at a fixed height of 0.9 m from a total of 215 trees from 47 open-pollinated families in a ten-year-old provenance-progeny trial of the species located at Boambee, at an altitude of 60 metres above sea level near Coffs Harbour, NSW. The core traits of basic density (unextracted), tangential shrinkage on drying at 70°C before reconditioning (BR), tangential shrinkage after steam reconditioning (AR) and tangential collapse recovery were found to be under strong genetic control, with moderate to high heritabilities.

A sub-sample of 40 of the sampled trees, with 1-2 trees from each of 27 open-pollinated families that were representative of the range of core shrinkage performance, was felled, and butt logs 2.4 m in length were back-sawn to produce a cant which yielded three to four 106 mm x 27 mm cross section boards per log for further processing. The boards were kiln-dried using an experimental schedule developed to express drying differences between families, steam reconditioned, and then scored for potentially value-limiting defects and graded according to the CSIRO Hardwood Appearance Product Assessment Criteria. The main results were:

- The most important board defects associated with the processing methods were (in order of importance) cupping, end-splitting and spring. Other potential drying defects of internal and surface checking did not cause significant degrade.
- There was an indication that cupping was under genetic control. Significant between-family differences were detected despite the small sample size.
- Significant differences among the 40 trees were also detected for spring and end-splitting, although significant differences among the families could not be demonstrated for these traits.
- Kino and decay were minor defects, and despite the stand being unpruned, over half of boards were graded as select grade or better, on knot criteria alone.
- Despite the poor drying performance primarily due to excessive cupping the results indicate that *E. dunnii* may prove to be suitable as a species capable of producing high-quality plantation-grown sawlogs, particularly if a slower drying schedule were applied.
- There were no strong relationships between core shrinkage properties and the value-limiting drying defects in the boards. There were few bands of pronounced shrinkage in the cores from above and below the boards, such as might be associated with severe board defects. There was little surface and internal checking of the boards, while core tangential shrinkage traits alone are less likely to explain cup, end-splitting and spring.
Silviscan traces from pith-to-bark wood strips taken at a height of 2.7 m, immediately above the sampled butt logs, displayed an increase in density and predicted dynamic modulus of elasticity from pith to bark, while microfibril angle (MFA) decreased from pith to bark. Crystallite width varied less in the radial direction, but frequently exceeded 3.6 nm, a value that may indicate the presence of tension wood. The Silviscan profiles were aligned with the images of matching pseudocore sections to examine the relationship between bands of shrinkage, both before and after reconditioning, and wood microstructure properties. It was concluded that changes in density, MFA and crystallite width were not reliable predictors of radial variation in core shrinkage properties, in part because pronounced radial change in shrinkage was rare.

Application of Results

We conclude that:

- Basic density and tangential shrinkage properties of wood cores do not appear to be reliable predictors of economically important drying defects for *E. dunnii* grown in the Boambee area.
- The 23-day kiln-drying schedule that was developed produced a high percentage of boards where cupping was a severe defect. Given that cupping appears to be under some degree of genetic control, there may be potential to genetically improve the *E. dunnii* resource so that it performs well under a similar drying schedule.
- Plantation-grown *E. dunnii* shows good potential for producing sawn timber, even from an unpruned resource, although light pruning would result in improved quality. Notably, defects such as kino and decay were uncommon.
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INTRODUCTION

Genetic improvement and silvicultural management of plantation eucalypts grown for solid and engineered-wood products are of increasing importance for Australia. In a recent survey, Nolan et al. (2005) estimated that 106,000 ha of Australian eucalypt plantations were being managed for sawlogs. The value of sawn timber, veneer and engineered-wood products such as plywood and laminated veneer lumber is determined by a complex interaction between the genetic material, site, silviculture and processing, and the demands of the market (Washusen et al. 2004). Improving the value of plantations producing these products, through silvicultural interventions and genetic improvement, presents many challenges, not least of which is the difficulty in accurately sampling wood quality to estimate, at acceptable cost, log and stand value for particular product types. One of the eucalypt species now widely planted in Australia is *Eucalyptus dunnii* Maiden, with over 8,000 ha of this species already planted in northern NSW by Forests NSW alone (M. Henson, pers. comm. 2005), hence there is keen interest in examining the solid-wood value of plantation-grown *E. dunnii* (Henson et al. 2004). Some basic information, including the susceptibility to Lyctid borers of the sapwood, relatively low durability making it unsuitable for external use, and an air-dry wood density of about 800 kg m$^{-3}$, is available for the timber of *E. dunnii* from native forests (Bootle 1983). It is noted that the species requires careful drying in the early stages to avoid checks and splits. However, *E. dunnii* has a very limited natural range in sub-coastal northern NSW and southern Queensland (Boland et al. 1984), and only very small volumes of the species are now harvested from native stands, so timber from natural stands is not widely used. It is not identified by the Australian Hardwood Network (www.australianhardwoods.net.au) as a species currently yielding commercial solid wood products.

Methodology for sampling eucalypt plantations to predict log and stand value of pulpwood is well-developed. Log value is determined primarily by volume, wood density and pulp yield, and protocols for predicting density and pulp yield from the density and pulp yield (predicted from NIR analysis) of wood cores taken at fixed height from sampled trees have been developed (Raymond and Muneri 2001, Raymond et al. 2001). Predictive equations relate wood core properties to corresponding log properties and hence value, with a known degree of precision, based on extensive sampling studies.

Analogous methods for predicting eucalypt solid-wood product value from small wood samples, or non-destructive assessment techniques, are less well-developed. This is due at least in part to the wider range of wood properties and defects that can impact on the recovery and grade, and hence value, of solid wood products (Raymond 2002). Board stiffness of *E. dunnii* was successfully predicted from sound frequencies of logs prior to sawing Dickson et al. (2002). In *E. globulus*, Yang and Fife (2003) found a strong relationship between tangential shrinkage before reconditioning (BR), measured on 20 mm (tangential) x 20 mm (radial) x 90 mm (longitudinal) blocks and the degree of internal checking of adjacent 38 mm thick backsawn boards, suggesting that check-prone trees of this species could be identified from the drying behaviour of small wood samples. In these trees this relationship was probably influenced by tension wood presence (Washusen and Ilic 2001). Variation in crystallite width in cell wall microfibrils, determined by SilviScan-2 (Washusen and Evans 2001b) reliably identifies tension wood in *E. globulus*, and has been shown to be a predictor of severe non-recoverable shrinkage in small wood samples in this species (Washusen and Evans 2001a). Sections of radial SilviScan sample profiles in *E. globulus* prepared from 12 mm increment cores with crystallite width exceeding about 3.6 nm indicate tension wood severity sufficient to cause distortion of sawn boards during drying (Washusen et al. 2004).
The main objective of the current project was to evaluate some low-cost methods of assessing solid-wood value of plantation-grown *E. dunnii* trees from the wood properties of increment cores. The hypothesis under test was that profiles of tangential shrinkage and collapse in increment cores taken at fixed height would predict levels of processing degrade in boards sawn from the corresponding log, and hence board value. Previous studies (Arnold et al. 2005) have already established that wood density and tangential shrinkage BR in increment cores are under strong genetic control in the progeny trial identified for this study. The study was also designed to determine suitable drying regimes and to provide basic information on the quality of kiln-dried sawn boards from young plantation-grown logs of the species.

**MATERIALS AND METHODS**

**Description of field trial and sampling strategy**

The trees selected for this study were growing in an *E. dunnii* provenance-progeny trial at Boambee, a low-elevation (60 m asl) coastal site near Coffs Harbour, NSW (Johnson and Arnold 2000). The trial site is close to, but not within, the natural range of occurrence of *E. dunnii*, the nearest natural stands occurring at Moleton, some 30 km distant and at an elevation of 500 masl. The Boambee trial tests 219 open-pollinated families of *E. dunnii*, collected from provenances across the species/natural range, and one control seedlot of *E. grandis*. The trial was planted in February 1995, at an initial espacement of 3 m x 2.4 m. Six replicates of 4-tree plots of each seedlot were established, using an incomplete block design for layout of treatments within replicates.

The trial was selectively thinned at age 4 years from an initial stocking of 1333 stems/ha to about 700 stems/ha, by reducing stocking of each 4-tree plot down to the best two trees, based on a combination of volume and stem form. At the time of sampling for this study, mean diameter at breast height (dbh) of the retained trees was 21.7 cm and mean height was 26.4 m (Henson et al. 2004). The stand had not been pruned, but *E. dunnii* tends to shed most of its lower branches when grown at initial close spacing (Figure 1).

A previous study on the trial (Arnold et al. 2005) which sampled 5 trees per family from each of 50 families had shown that the traits of core basic density and core maximum tangential recoverable collapse at age six years were under strong genetic control, having within provenance individual-tree heritabilities of 0.42 and 0.75 respectively, assuming a coefficient of relationship within open-pollinated families of 0.4. In this study, 0.9 m had been identified as an optimal sampling height for predicting whole-tree density from the density of a fixed-height core. Results from this study were used to identify families with high and low overall core shrinkage (shrinkage plus recoverable collapse). Three high-shrinkage and three low shrinkage families, together with 41 other families displaying good volume growth in the trial, were selected for inclusion in this study. Table 1 shows the CSIRO collection numbers, and number of families per collection included in the study. The CSIRO collections were grouped into 10 local geographic provenances as indicated in Table 1.

Trees sampled were dominant or co-dominant, of reasonable straightness and without major defects in the lower log. Trees came from among those about to be felled by Forests NSW for further development of the stand, and each of the sampled trees was the second best tree
(judged subjectively on the basis of a combination of bole volume, straightness and visible log defects) in its 4-tree family plot, with two inferior trees having been felled at age 4 years.

The sampling constraints led to a lower sampling intensity for some families than the 5 trees per family that had been planned. A total of 215 trees were cored for the study, comprising 3, 4 or 5 trees from each of 47 families. Thirty families contributed 5 trees, 14 families contributed 4 trees and 3 families contributed 3 trees. Mr KMA Bandara of the Australian National University visited the site in December 2003, and, assisted by Forests-NSW staff led by Mr Steve Boyton, made final selections of trees for inclusion in the study and conducted sampling of increment cores.

Table 1. Families of *E. dunnii* sampled in the study

<table>
<thead>
<tr>
<th>CSIRO seedlot no.</th>
<th>Provenance no. and name</th>
<th>Latitude (°S)</th>
<th>Longitude (°E)</th>
<th>Altitude (m)</th>
<th>No. of families sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>17909</td>
<td>1 Yabbra SF</td>
<td>28°35</td>
<td>152°29</td>
<td>565</td>
<td>2</td>
</tr>
<tr>
<td>17911</td>
<td>2 Spicers Ck SF</td>
<td>28°04</td>
<td>152°24</td>
<td>675</td>
<td>2</td>
</tr>
<tr>
<td>17914</td>
<td>3 Teviot Falls</td>
<td>28°13</td>
<td>152°32</td>
<td>360</td>
<td>1</td>
</tr>
<tr>
<td>17920</td>
<td>4 Acacia Ck</td>
<td>28°24</td>
<td>152°20</td>
<td>685</td>
<td>3</td>
</tr>
<tr>
<td>17922</td>
<td>5 Kangaroo R</td>
<td>30°05</td>
<td>152°54</td>
<td>420</td>
<td>4</td>
</tr>
<tr>
<td>18263</td>
<td>1 Yabbra SF</td>
<td>28°35</td>
<td>152°29</td>
<td>565</td>
<td>4</td>
</tr>
<tr>
<td>18264</td>
<td>6 Yabbra Plains</td>
<td>28°37</td>
<td>152°29</td>
<td>500</td>
<td>6</td>
</tr>
<tr>
<td>18735</td>
<td>7 Koreelah</td>
<td>28°16</td>
<td>152°32</td>
<td>625</td>
<td>2</td>
</tr>
<tr>
<td>18736</td>
<td>8 Beaury SF</td>
<td>28°30</td>
<td>152°22</td>
<td>560</td>
<td>3</td>
</tr>
<tr>
<td>18737</td>
<td>7 Koreelah</td>
<td>28°16</td>
<td>152°32</td>
<td>625</td>
<td>3</td>
</tr>
<tr>
<td>18739</td>
<td>9 Haystack E. Yabbra SF</td>
<td>28°36</td>
<td>152°30</td>
<td>550</td>
<td>1</td>
</tr>
<tr>
<td>18740</td>
<td>10 Moleton</td>
<td>30°09</td>
<td>152°53</td>
<td>500</td>
<td>4</td>
</tr>
<tr>
<td>18756</td>
<td>4 Acacia Ck</td>
<td>28°24</td>
<td>152°20</td>
<td>685</td>
<td>3</td>
</tr>
<tr>
<td>18757</td>
<td>7 Koreelah</td>
<td>28°16</td>
<td>152°32</td>
<td>625</td>
<td>6</td>
</tr>
<tr>
<td>18758</td>
<td>10 Moleton</td>
<td>30°09</td>
<td>152°53</td>
<td>500</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>47</td>
</tr>
</tbody>
</table>

Sampling and analysis of wood cores from sampled trees

One 12 mm diameter increment core was taken from each sampled tree at a height of 0.9 m above ground in a north-south direction using a “Trecor” motor-driven tree-coring bit. An exception to this was in Replicate 5 where an east-west direction was chosen for ease of coring because of sloping terrain. Cores were labelled and stored in zip-lock plastic bags to prevent drying, stored temporarily in an ice box at around 4°C, and taken to Canberra where they were stored at 2°C prior to drying.

Core green volumes were measured using the water displacement method (Kollman and Côté 1968). Initial drying trials were carried out on a small additional set of cores to optimise drying conditions. It was found that drying in an oven with forced air movement for 48 hours at 70°C gave the clearest expression of shrinkage and recoverable collapse. Cores were constrained in aluminium “U” channelling of internal width 13 mm, with the longitudinal axis of the wood oriented vertically, so as to maintain their straightness during drying.
Immediately after drying at 70°C, minimum tangential diameter on either side of the central pith was measured to the nearest 0.1 mm, using vernier callipers. Core tangential profiles were then scanned using a high-resolution flat-bed scanner. Files of individual core scans were edited to convert them to 8-bit grey-scale and sections with splits and breaks removed prior to image analysis. Profiles of core tangential diameter were obtained using an image analysis routine provided by Dr Rob Evans of CSIRO Forestry and Forest Products.

Cores were then steam-reconditioned by holding them in a rack above boiling water at atmospheric pressure for 1.5 hours. Minimum tangential diameter on either side of the core was re-measured, and the cores were re-scanned. Finally, cores were oven dried and weighed to enable calculation of basic density from the ratio of oven-dry weight to green volume (Kingston and Risdon 1961). Table 2 summarises the core traits that were measured and analysed.

Table 2. Summary of core traits that were measured and analysed

<table>
<thead>
<tr>
<th>Trait</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Basic density (kg m⁻³)</td>
<td>Calculated from core green volume and oven-dry weight</td>
</tr>
<tr>
<td>2. Min. core diameter</td>
<td>Mean of minimum tangential diameters on either side of the central</td>
</tr>
<tr>
<td>before recon.</td>
<td>pith measured using vernier callipers, after drying and before</td>
</tr>
<tr>
<td>after recon.</td>
<td>reconditioning</td>
</tr>
<tr>
<td>3. Min core diameter</td>
<td>Mean of minimum tangential diameters measured using vernier</td>
</tr>
<tr>
<td>after recon.</td>
<td>callipers on either side of the pith, after reconditioning</td>
</tr>
<tr>
<td>4. Collapse recovery (mm)</td>
<td>Recovered collapse, estimated as the difference between trait 3 and</td>
</tr>
<tr>
<td></td>
<td>trait 2 (mean of two sides).</td>
</tr>
<tr>
<td>5. Mean scanned core</td>
<td>Mean diameter obtained by image analysis from scanned tangential</td>
</tr>
<tr>
<td>diameter before recon.</td>
<td>image of core after drying and before reconditioning</td>
</tr>
<tr>
<td>6. Mean scanned core</td>
<td>Mean diameter obtained by image analysis from scanned tangential</td>
</tr>
<tr>
<td>diameter after recon.</td>
<td>image of core after reconditioning</td>
</tr>
</tbody>
</table>
The core variates shown in Table 2 were analysed statistically using Genstat 7.0 software (Genstat 2000). Preliminary analysis indicated that replicate differences were not significant for most of the core variates, so replicate was omitted from the statistical model since it was partially confounded with family differences (due to some families being represented in only 3 or 4, rather than 5 replicates). A model with seed source (provenance) as a fixed effect and family within seed source as a random effect was used. Within-seed source heritabilities and their standard errors were calculated according to the method of Williams et al. (2002), assuming a coefficient of relationship for open-pollinated families of 0.4, reflecting a degree of inbreeding resulting from self-fertilization and neighbourhood inbreeding common to natural stands of most eucalypt species studied to date (Eldridge et al. 1993). No specific information is available on levels of inbreeding in natural populations of E. dunnii. Genetic correlations among traits were calculated using ASReml using the same statistical model.

**Sawing and additional sampling of subset of 40 trees**

The 215 trees were ranked according to their minimum tangential core diameters following drying and prior to reconditioning (Trait 2, Table 2) and a stratified sample of 40 trees, sampled to give a distribution of minimum tangential core diameters representative of that in the overall population of 215 trees, was selected for processing into solid wood products.

Figure 2 summarises the sampling carried out for the study. The heights and diameters of the 40 trees selected for processing are shown in Table 3.
Figure 2. Summary of wood and log sampling for the study

Table 3. Mean, minimum and maximum total tree height, diameter at breast height (Dbh) over bark, and height/Dbh ratio for the 40 trees felled and sawn in the study.

<table>
<thead>
<tr>
<th></th>
<th>Height (m)</th>
<th>Dbh (cm)</th>
<th>Height / Dbh ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>29.6</td>
<td>25.3</td>
<td>1.17</td>
</tr>
<tr>
<td>minimum</td>
<td>22.1</td>
<td>16.5</td>
<td>0.92</td>
</tr>
<tr>
<td>maximum</td>
<td>32.9</td>
<td>34.8</td>
<td>1.41</td>
</tr>
</tbody>
</table>

The 40 selected trees were felled in late January 2004, and a 2.4 m sawlog was cut from each tree. The base of each sawlog was at 0.2-0.3 m above ground. Disks, 50 mm in thickness, were cut from above and below each sawlog, wrapped in plastic and transported to Canberra,
where they were stored at 2°C prior to processing. Logs were transported to the Boral Sawmill, Koolkhan. Each log was back-sawn to produce a cant with a central axis running in the north-south plane in the standing tree. Boards from the central cant were numbered using the log end templates to identify boards from the north and south side of the log and position relative to the pith. The central board containing most of the pith was eliminated leaving a set of three or four 106 x 27 mm green dimensioned boards from each log. Dr Russell Washusen, Mr KMA Bandara, Mr Steve Boyton and Dr Geoff Smith supervised the felling and sawing work, which was carried out on January 22-23, 2004. Bow and spring were measured on each board immediately after sawing. The boards were wrapped in plastic to minimise moisture loss and road freighted to Clayton where they were placed in cold (2°C) storage prior to drying.

From each of the disks above and below each log, a 12 mm x 12 mm “pseudocore” was cut using a bandsaw. The pseudocores were cut in a north-south orientation such that their bark-to-bark axis ran parallel to the 100 mm faces of the set of backsawn boards.

The pseudocores were wet-sanded to smooth the tangential faces, scanned, and then dried at 70°C and reconditioned in steam as per the initial set of cores. Measurements of tangential width were made with vernier callipers at 12 equidistant marked points along each lower pseudocore and 10 equidistant points along each upper pseudocores, before drying, after drying and after reconditioning. From these measurements, shrinkage BR, shrinkage AR and recovered collapse were calculated for each marked point. They were converted to percentages for further analysis, as the green tangential widths of the pseudocores varied slightly. Figure 3 shows pseudocores constrained in the aluminium channelling, after drying at 70°C for 48 hours and before reconditioning.

The pseudocores were scanned to display their tangential profiles while still green, scanned again after drying at 70°C, and then stem-reconditioned and re-scanned. The scanned images were prepared for automatic image analysis as in the cores study. The scanned images of the upper and lower pseudocores of all 40 trees sampled for sawing are shown in Appendix 1.
Figure 3. Pseudocores constrained in aluminium channelling after drying at 70°C, showing marked points for tangential width measurement. Internal width of aluminium channelling is 13 mm.

**Processing and scoring of boards**

The boards from the 40 sawn trees were stored green, wrapped in plastic at 2-4°C, at CSIRO’s Clayton laboratories until kilns became available for drying. Currently there are no published kiln drying schedules for *E. dunnii* so before the boards were kiln dried in a pilot scale industrial kiln an experimental drying schedule was trialled in a laboratory kiln. For this work, 20 boards containing mostly outer heartwood and sapwood were selected from the south side of 20 logs that represented the linear tangential shrinkage range BR in the cores. From the 20 boards a subset of board sections 0.8 m in length were cut from the middle of each board and these were dried in the experimental kiln after determining moisture content (MC) from two cross-sections. The MC, dry bulb temperature (DBT) wet bulb temperature (WBT) and air-speed were recorded during drying. The drying conditions were adjusted after monitoring defect development on boards. The experimental schedule and MC of boards are shown in Figure 4. The MC at start of drying was 114% and at completion 11%. During the initial stages of drying the wet bulb dried out and kiln control was lost temporarily producing a
larger wet bulb depression (WBD) than planned. After 19 days board MC was 33%, even so the drying schedule produced drying performance that was variable from board to board, and even harsher conditions were considered suitable for assessing differences between trees in the full set of boards.

Figure 4. Experimental drying schedule established for plantation-grown *E. dunnii* in the laboratory kiln, and board moisture content during drying.

The schedule applied to the full-length boards was a slightly elevated temperature schedule that has good potential to be applied by industry on a commercial scale. It was applied primarily to produce drying differences between trees, such as might arise from genetic differences or local environmental differences within the stand. Before drying commenced the boards were distributed randomly in the drying stack. During the drying the kiln was not operational for short periods when steam was not available and for an extended period late in the drying process when the kiln variable speed drive failed. During the drying phase when the DBT was between 45-70 °C the schedule incorporated high humidity treatments for 1 hour every 8 hours by injection of steam. MC, DBT, WBT and air-speed were recorded during drying. As with the laboratory schedule the conditions produced varied drying defects ranging from no defects to severe drying defects. At approximately 14% MC the boards were steam-reconditioned in the kiln for 6 hours, followed by further drying for 3 days. Figure 5 plots the MC and temperature conditions during drying and shows the location of interruptions to the schedule.
Figure 5. Kiln drying schedule used for drying the boards, and board moisture content during drying.

Scoring of the reconditioned boards was conducted over the period October 18-21, 2004. Boards were classified as to whether their two ends and/or mid-length were perfectly back-sawn, or sawn with a mixed growth ring orientation (back/quartersawn), and whether or not the upper or lower end and/or mid-length of each board included the central pith, the presence of which was typically associated with distortion on drying and severe surface defects. A total of 142 boards were then measured for the following potentially value-limiting defects: cup, bow, spring, end-splitting, surface checking and internal checking (the latter determined on cross cut surfaces at the mid length), and non-recoverable collapse. Spring was assessed both on the uncut 2.4 m board and on the two 1.2 metre-long halves.

Statistical analysis of the board defect data, and its relationship to wood core properties from the 40 sawn trees, was carried out using Genstat 7.0. Analysis of the individual board traits was carried out to determine whether open-pollinated families and trees within families differed significantly in their board properties, using variation among boards within trees to generate the residual variance stratum. These analyses were carried out using generalised linear models with the FIT command in Genstat, modelling family and tree-within-family as fixed effects, in that order. Many of the board variables were non-normally distributed, with many boards displaying zero level of the defect, some having moderate defect and a few boards showing severe defect. Square-root and logarithmic transformations ((log (value +1)) were conducted where appropriate to obtain better approximations of normal distributions of the residual errors, and binomial analyses based on presence/absence of the defect were also conducted for some variates. The data was first analysed using FIT with a simple model, fitting only trees as a fixed effect, to test between-tree differences in board performance. For those variates where trees differed significantly, differences between families were judged
significant where the between-trees mean square was similar to the boards-within-trees mean square that was used as the denominator for the F-ratio tests, so that a variance ratio using the between-trees mean square as a denominator and the between-families mean square as a numerator returned a significant probability.

To quantify the level of defect in each 1.2 long section of the boards they were graded using the CSIRO Hardwood Appearance Product Assessment Criteria, which are shown in Appendix 1. To do this each of the defect categories observed on the boards were graded. These defects were pith, spring, cupping, internal checking, surface checking, knots, wane, kino and decay. To enable the application of this criterion the length restrictions that are normally imposed on some grades were abandoned. The CSIRO criteria applied in this way produces recoveries similar to the way many mills apply the current Australian Standard (AS 2796). The percentages of boards in each product class for each of the defects were calculated.

**SilviScan analysis**

From each upper disk a second pseudocore, located vertically above the first, was cut and prepared for SilviScan analysis. These pseudocores were successively dehydrated by soaking for three days in each of 70, 90% and 100% ethyl alcohol solutions. They were then dried for two months in a controlled environment drying room to 12% moisture content. The pseudocores were mounted on wood flitches and a 2 mm (tangential) x 8 mm (longitudinal) bark-to-bark strip was cut using a twin-bladed saw. Each strip was cut into two pith-to-bark halves. For each tree, one pith-to-bark strip was selected for SilviScan analysis, preference being given to the one with no defects. Sample strip lengths ranged from 53 to 145 mm with a mean length of 100 mm.

The 40 SilviScan pith-to-bark samples were analysed using SilviScan 2 (Evans et al. 2000; Washusen and Evans 2001a, 2001b) to give estimates of the following wood microstructure properties:

- Density; the mean value for each 50 micron section along the radial profile
- Microfibril angle; the mean value for each 0.5 mm strip section
- Cellulose crystallite width; the mean value for each 0.5 mm strip section
- Modulus of elasticity; the mean value for each 0.5 mm strip section

The dynamic modulus of elasticity is a derived variate calculated from density and the variation in intensity of the azimuthal scan (Evans and Ilic 2001)

**RESULTS**

**Wood core properties**

Table 4 shows the overall mean and range of family means of the different core traits, and the individual-tree heritabilities. Genetic correlations among the core traits are shown in Table 5.
Table 4. Range of variation in core wood traits, significance of differences between provenances and within-provenance heritabilities

<table>
<thead>
<tr>
<th>Variate</th>
<th>Overall mean, and range of family means</th>
<th>F-probability for significance of differences between seedlots*</th>
<th>Within-provenance heritability**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Basic density (kg m(^{-3}))</td>
<td>481.9 (416.8-514.7)</td>
<td>n.s.</td>
<td>0.55 (0.23)</td>
</tr>
<tr>
<td><strong>Measured by callipers</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Min. core diameter BR (mm)</td>
<td>9.76 (8.17-9.89)</td>
<td>&lt;.05</td>
<td>0.63 (0.24)</td>
</tr>
<tr>
<td>3. Min core diameter AR (mm)</td>
<td>10.60 (9.53-11.12)</td>
<td>n.s.</td>
<td>0.30 (0.18)</td>
</tr>
<tr>
<td>4. Collapse recovery (mm)</td>
<td>1.34 (1.15-1.81)</td>
<td>&lt;.05</td>
<td>0.57 (0.23)</td>
</tr>
<tr>
<td><strong>From scans of cores</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Mean scanned core diameter BR</td>
<td>10.11 (9.54-10.55)</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>6. Mean scanned core diameter AR</td>
<td>11.14 (11.02-11.38)</td>
<td>&lt;.01</td>
<td>0.26 (0.18)</td>
</tr>
</tbody>
</table>

*n.s. not significant
**individual-tree, assumes coefficient of relationship within families = 0.4

Table 5. Genetic (above the diagonal) and phenotypic (below the diagonal) correlations between density and shrinkage properties (average tangential collapse recovery and average tangential shrinkage AR from image analysis)

<table>
<thead>
<tr>
<th>Density</th>
<th>Tangential collapse%</th>
<th>Tangential shrinkage%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>-0.94±0.20</td>
<td>-0.19±0.47</td>
</tr>
<tr>
<td>Tangential collapse recovery %</td>
<td>-0.37±0.06</td>
<td>0.59±0.61</td>
</tr>
<tr>
<td>Tangential shrinkage AR %</td>
<td>0.19±0.07</td>
<td>-0.17±0.47</td>
</tr>
</tbody>
</table>

Mean basic density of the cores was 481.9 kg m\(^{-3}\). Basic density was under strong genetic control, as were most of the shrinkage and collapse traits. Differences between provenances were significant (P<.05) for collapse recovery, minimum core diameter BR, and mean and minimum scanned core diameter AR, but not for the other variates.

Within-provenance heritabilities for most of the core traits were moderate-to-high (range 0.26-0.63), and were greater than their standard errors. The exception was mean scanned core diameter before reconditioning, with a non-significant heritability. There was a strongly negative genetic correlation between core basic density and mean collapse recovery.

Results obtained were similar to those obtained from the same trial at age 6 years by Arnold et al. (2005). In their study, family mean core densities at Boambee varied from 418 to 516 kg m\(^{3}\), with an overall mean of 466 and a within provenance heritability of 0.42. Family mean shrinkage BR varied more widely in their study, from 0.6 mm to 4.4 mm, with a higher heritability (0.75). Their cores were dried to 105°C BR, and the single point of minimum tangential diameter after drying and BR, termed collapse, was the assessed variable.

In summary, the results of our study of increment cores confirmed the previous finding of Arnold et al. (2005) that wood basic density and wood tangential shrinkage properties of *E. dunnii*, as indicated by core density and core shrinkage properties, are under strong genetic
control. The next step in the investigation was to examine whether variation in these properties relates to variation in properties of sawn boards, at the individual tree and individual board level.

**Board properties**

Table 6 summarises the assessments and measurements made on the boards, together with the mean, minimum and maximum values for individual boards and the number of observations for each variate. The shrinkage measurements for the individual measurement points of the basal and upper pseudocores located closest to the lower and upper ends respectively of the boards from each log, expressed as percentages, are also shown.

Considering the means and ranges in Table 6, it is evident that for many of the defects that were scored, the boards are relatively free of value-limiting levels of defect. The most serious defects were judged to be cup, end-splitting and spring in declining order of severity. The mean cup depth 3.05 mm indicated that cupping was the most serious defect (Figure 6). In 25 mm thick boards this level of cupping would result in considerable down-grade of product even if boards were dressed to 19 mm, i.e. removal of 6.0 mm of wood will still result in about 50% of boards being undersized.

Significant differences between families were demonstrated for some of the individual board variates, as summarised in Table 7. The interpretation of analyses is complicated by the issues of whether to exclude data points from boards and board ends containing pith, or mixed quarter/back sawn boards, and the appropriate transformations to use for non-normally distributed variates. For the board-end-specific traits, values were excluded from board-halves that contained central pith for the relevant half of the board. For total bow and spring, values were excluded from boards that had pith at either end of the entire 2.4 m board. For spring in green boards, a binomial analysis based on presence/absence of spring was required as transformations could not stabilise the distribution of residual errors. Analysis of the other traits presented in Table 7 used non-transformed data.

Cupping of the lower ends of the boards appears to be under some degree of genetic control, with significant differences in this trait among open-pollinated families (Table 7, Table 8). The distribution of residual errors for the non-transformed cupping data closely approximated a normal distribution and thus satisfied the basic assumptions of analysis of variance (Williams et al. 2002). For total spring of green boards, and after conditioning total spring, spring in the bottom half of the boards, and end-splitting, there were statistically significant differences among the 40 trees, but we were unable to establish the significance of differences among families, relative to differences among trees within families. Excluding 2-3 outlying data points for the end-splitting traits improved the plots of residual errors, and increased the significance of between-tree differences.
### Table 6. Mean, maximum and minimum values, and number of observations for each assessed board traits and the associated shrinkage traits of the pseudocores

<table>
<thead>
<tr>
<th>Trait</th>
<th>mean</th>
<th>maximum</th>
<th>minimum</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bow of green boards (mm)</strong></td>
<td>17.2</td>
<td>60</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td><strong>Spring of green boards (mm)</strong></td>
<td>3.5</td>
<td>20</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td><strong>Board traits after conditioning</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bow (mm)</td>
<td>5.25</td>
<td>25</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td>Spring (total board) (mm)</td>
<td>6.85</td>
<td>34</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td>End split length basal end of board (mm)</td>
<td>95.32</td>
<td>910</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td>End split length top end of board (mm)</td>
<td>122.2</td>
<td>600</td>
<td>0</td>
<td>141</td>
</tr>
<tr>
<td>Cup at basal end of board (mm)</td>
<td>3.21</td>
<td>9</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td>Cup at top end of board (mm)</td>
<td>2.90</td>
<td>10</td>
<td>0</td>
<td>125</td>
</tr>
<tr>
<td>Spring in basal half of board (mm)</td>
<td>3.19</td>
<td>14</td>
<td>0</td>
<td>125</td>
</tr>
<tr>
<td>Spring in upper half of board (mm)</td>
<td>2.17</td>
<td>16</td>
<td>0</td>
<td>123</td>
</tr>
<tr>
<td>Maximum width of surface checking in basal half of board (mm)</td>
<td>0.24</td>
<td>3</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td>Maximum width of surface checking in upper half of board (mm)</td>
<td>0.20</td>
<td>3</td>
<td>0</td>
<td>124</td>
</tr>
<tr>
<td>Surface checking grade for basal half of board 1-6 scale, 6 worst</td>
<td>1.69</td>
<td>6</td>
<td>1</td>
<td>142</td>
</tr>
<tr>
<td>Surface checking grade for upper half of board 1-6 scale, 6 worst</td>
<td>1.46</td>
<td>6</td>
<td>0</td>
<td>125</td>
</tr>
<tr>
<td>Unrecoverable collapse length of section for basal half of board (mm)</td>
<td>255.9</td>
<td>1200</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td>Unrecoverable collapse length of section for upper half of board (mm)</td>
<td>144.6</td>
<td>1200</td>
<td>0</td>
<td>125</td>
</tr>
<tr>
<td>Number of internal checks at midpoint of board</td>
<td>0.04</td>
<td>2</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td>Total length of internal checks (mm)</td>
<td>0.29</td>
<td>15</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td>Mean width of internal checks (mm)</td>
<td>0.03</td>
<td>1.5</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td><strong>Pseudocore traits</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tangential shrinkage BR of basal pseudocore at nearest point to board (%)</td>
<td>19.04</td>
<td>29.88</td>
<td>5.8</td>
<td>141</td>
</tr>
<tr>
<td>Tangential shrinkage AR of basal pseudocore at nearest point to board (%)</td>
<td>7.17</td>
<td>14.84</td>
<td>3.49</td>
<td>141</td>
</tr>
<tr>
<td>Tangential collapse recovery of basal pseudocore at nearest point to board (%)</td>
<td>11.87</td>
<td>23.25</td>
<td>1.51</td>
<td>141</td>
</tr>
<tr>
<td>Tangential shrinkage BR of upper pseudocore at nearest point to board (%)</td>
<td>15.76</td>
<td>43.04</td>
<td>5.08</td>
<td>141</td>
</tr>
<tr>
<td>Tangential shrinkage AR of upper pseudocore at nearest point to board (%)</td>
<td>7.13</td>
<td>13.27</td>
<td>1.79</td>
<td>141</td>
</tr>
<tr>
<td>Tangential collapse recovery of upper pseudocore at nearest point to board (%)</td>
<td>8.63</td>
<td>31.25</td>
<td>1.69</td>
<td>141</td>
</tr>
</tbody>
</table>
Figure 6. Cupping and end-splitting visible in stacked boards after kiln-drying and reconditioning.

Table 7. F-probabilities of significance of between-family and between-tree differences for spring, cup and end split at the top and bottom ends of the boards. Boards with central pith excluded.

<table>
<thead>
<tr>
<th>Variate</th>
<th>Significance of differences between families</th>
<th>Significance of difference between trees (family excluded from statistical model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green spring†</td>
<td>n.s.</td>
<td>***</td>
</tr>
<tr>
<td>After conditioning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total spring</td>
<td>n.s.</td>
<td>*</td>
</tr>
<tr>
<td>Total bow</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>Spring, bottom half</td>
<td>n.s.</td>
<td>*</td>
</tr>
<tr>
<td>Cup, bottom half</td>
<td>**</td>
<td>*</td>
</tr>
<tr>
<td>End split, bottom end</td>
<td>n.s.</td>
<td>**</td>
</tr>
<tr>
<td>Spring, top half</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>Cup, top half</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>End split, top end</td>
<td>n.s.</td>
<td>*</td>
</tr>
</tbody>
</table>

Chi-squared probability based on binomial analysis of presence/absence of spring in green boards
Table 8. Analysis of variance for cupping at the base of the boards, showing significance of between-family differences, and plot of residual errors

<table>
<thead>
<tr>
<th>Change</th>
<th>d.f.</th>
<th>s.s.</th>
<th>m.s.</th>
<th>v.r.</th>
<th>F pr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ family</td>
<td>26</td>
<td>87.732</td>
<td>3.374</td>
<td>2.30</td>
<td>0.002</td>
</tr>
<tr>
<td>+ tree</td>
<td>13</td>
<td>24.293</td>
<td>1.869</td>
<td>1.27</td>
<td>0.244</td>
</tr>
<tr>
<td>Residual</td>
<td>94</td>
<td>138.104</td>
<td>1.469</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

d.f. = degrees of freedom, s.s. = sum of squares, m.s. = mean square, v.r. = variance ratio, F pr. = F probability

Board grading to appearance products

The percentage allocation of boards to different appearance grade categories is shown in Table 9. The criterion for cupping (not shown in Appendix 1) was that boards with cupping of greater than 2.5 mm were classed as rejects. Board length was not addressed specifically as a grading criterion; rather it was assumed that end-splits were docked reducing board lengths as noted above. Further, it was assumed that the boards had been treated with preservative, so presence of Lyctid-susceptible sapwood was not assessed as a potential grading defect.

Table 9. Board allocation to different product classes for each grading defect, using CSIRO Appearance Grade Criteria. Percent allocations to different product classes are shown.

<table>
<thead>
<tr>
<th>Pith</th>
<th>Spring</th>
<th>Cup</th>
<th>Surface checking</th>
<th>Internal checking</th>
<th>Knot</th>
<th>Wane</th>
<th>Kino</th>
<th>Decal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polish</td>
<td>77.8</td>
<td>75.3</td>
<td>29.4</td>
<td>70.6</td>
<td>96.5</td>
<td>14.9</td>
<td>91.2</td>
<td>96.9</td>
</tr>
<tr>
<td>Select</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>2.1</td>
<td>2.1</td>
<td>37.6</td>
<td>0.0</td>
<td>2.6</td>
</tr>
<tr>
<td>Standard</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>19.1</td>
<td>0.5</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Utility</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>7.2</td>
<td>0.5</td>
<td>14.4</td>
<td>14.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Cover</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>30.4</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Reject</td>
<td>22.2</td>
<td>24.7</td>
<td>70.6</td>
<td>0.0</td>
<td>0.0</td>
<td>1.5</td>
<td>3.6</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The results of the board grading (Table 9) confirm that cupping was the most important defect in reducing board grade, with over 71% of boards having unacceptable degree of cupping (greater than 2.5 mm at some point along the board), leading to their rejection. Spring, and surface defects associated with pith, would have led to grading of 22% and 25% of boards respectively as reject category. Knots, while visible on many of the boards (Figure 7), were mostly small, sound or located on the backs of boards (in the case of select, standard and utility grades), and over half of the boards were graded as select grade or better with regard to knots, most of the balance being graded as utility and cover. This result confirms the observations at harvest that the lower bole was relatively free of branches and that this species appears to shed branches readily. Even so, had pruning been conducted, the percentage of clear grade boards (polishing grade) would have been greater and utility and cover grades lower. Surface and internal checking, wane, kino and decay did not lower product grade substantially. Across the 40 logs, mean length of end-splitting, combining end-splitting at both the top and bottom of the boards, amounted to 218 mm, which would remove about 10% of total board length if end-splits were docked.
Figure 7. View of board faces after kiln drying and before reconditioning, showing typical appearance of knots. Holes from 0.9 m increment cores visible on some boards.

Relationships between core traits and board traits

As with the analyses of individual board traits, determination of relationships between core properties and board traits is complicated by the issue of whether to exclude data from board sections that contain the central pith or are mixed (back/quarter) sawn. Figure 8 shows the relationships between basal cupping of the boards and percentage tangential shrinkage BR of the matched pseudocore sections. Figure 9 shows the relationship between basal cupping and the basic density of the fixed height increment cores taken at 0.9 m. The data points associated with basal board-halves containing the central pith are excluded from these graphs. Regression lines and equations are not shown because the linear regressions are not significant. Several outlying data points strongly influence the relationships, but it is evident that there is no clear predictive relationship between tangential shrinkage BR of matching pseudocore sections and board cupping, or between fixed-height core basic density and cupping. No significant relationships could be determined between core traits and the other major board defect traits of end-splitting, spring and surface checking,
Figure 8. Relationship between cupping at the base of the board and tangential shrinkage of the corresponding section of the matched adjacent pseudocore.

Figure 9. Relationship between cupping at the bottom of the board and basic density of corresponding fixed-height core taken at 0.9 m.

SilviScan analysis traits and their relationship to core tangential shrinkage properties

Figures 10-13 provide a convenient overview of the SilviScan results obtained. For all 40 samples, the four SilviScan variates are plotted out, showing the means of 10 mm sections from pith to bark. The first position, at 0 cm on the graph, is the mean for a residual fraction of 10 mm, because the SilviScan analysis actually commences at the bark end of the strip. 40 points are therefore displayed for the inner positions, starting from the pith (0 cm), and progressively fewer points at the outer positions, as the samples with shorter length run out.
Figure 10. Radial variation in density in pith-to-bark sections from immediately above the sawn boards of the 40 sampled logs

Figure 11. Radial variation in microfibril angle in pith-to-bark sections from immediately above the sawn boards of the 40 sampled logs
Figure 12. Radial variation in predicted dynamic modulus of elasticity in pith-to-bark sections from immediately above the sawn boards of the 40 sampled logs.

Figure 13. Radial variation in cellulose crystallite width in pith-to-bark sections from immediately above the sawn boards of the 40 sampled logs.
The overall radial trends in wood microstructure variation are consistent with those observed for other eucalypt species such as *E. nitens* (Evans and Ilic 2001, Evans et al. 2001). Density increases from pith to bark, particularly in the wood beyond 3 cm from the pith, which would have been laid down from year 2-3 onwards. Microfibril angle decreases from pith to bark, while predicted modulus of elasticity increases, a consequence of the decrease in MFA and increase in density. Cellulose crystallite width is relatively stable, within the range 3-4 nm. Many of the 1 cm mean values for crystallite width exceed 3.6 nm, suggesting that significant amounts of tension wood may be present (Washusen and Evans 2001a, 2000b).

Figure 14 displays the detailed SilviScan trace for one of the individual samples, together with the tangential image scan of the matching pith-to-bark section of the corresponding pseudocore. It is apparent from examination of this density scan, and that of the other 39 logs, that the peaks in density do not correspond exactly to annual bands of latewood as is typically found in *E. globulus* and *E. nitens* growing in southern Australia and experiencing cool to cold winters (Evans et al. 2000, Washusen et al. 2004). At least 12 peaks of density can be seen in Figure 14, and the tree was less than 10 years old when harvested. Whether these peaks of density correspond mainly to seasonal slowing in growth during the cooler winter months, or to periods of lower water availability that typically occur in late winter early spring is not known. Narrow shrinkage bands at around 70 mm from the pith occur at the same place as sharp changes in wood density at this position, but there are no associated changes in crystallite width or MFA.

Examination of the tangential image scans after drying and before reconditioning for the upper pseudocores of the 40 trees showed that there were very few bands of severe shrinkage BR, as might be generated by bands of tension wood (Washusen et al. 2004). The scan images generally showed only gradual changes in shrinkage along the core. Typical examples are shown in Appendix 2. Examination of the traces from SilviScan generally shows only minor changes of 0.1 to 02 nm in crystallite width between successive 5 mm sections of the traces.
DISCUSSION

Highly significant genetic control of wood basic density and tangential shrinkage properties in the sample of fixed-height increment cores from 215 trees was demonstrated for E. dunnii, confirming the earlier results of Arnold et al. (2005) for a different set of 50 families from the same trial at age 6 years. Kube and Raymond (2005, in press) similarly found high heritability for wood basic density and tangential collapse recovery in open-pollinated progeny trials of E. nitens. Given the high heritability for core basic density, and the substantial variance of this trait, with family means ranging from 417 to 515 kg m\(^{-3}\), there is excellent potential for genetic improvement to increase wood density for the species. Cylindrical cores over-sample the inner wood, which is of lower density than the outer wood (Figure 10). Thus, the mean basic density of 482 kg m\(^{-3}\) estimated from the fixed-height cores in this study would be a slight under-estimate of the true basic density of the logs. Henson et al. (2004) estimated density from wood disks from 179 butt-logs of E. dunnii harvested from the Boambee trial at the same time as our study, and obtained a slightly higher value for mean basic density of 514 kg m\(^{-3}\). This value corresponded closely to the mean basic density of 508 kg m\(^{-3}\) estimated for 5.8 m butt-logs from a 9-year-old E. dunnii plantation at nearby Newry State Forest, obtained by Dickson et al. (2002). These authors found the density of older, 25-year-old E. dunnii logs to average 600 kg m\(^{-3}\). Increasing basic density would lead to concomitant improvement in wood stiffness (Dickson et al. 2002), although Dickson et al. noted that the E. dunnii boards in their study generally exceeded the stiffness thresholds for structural application. The strongly negative genetic correlation (-0.94) between basic density and mean tangential collapse recovery, determined for the cores, is also favourable, as selecting for higher density would reduce collapse. Kube and Raymond (2005) found a similarly favourable (negative) correlation between basic density and shrinkage BR for plantation-grown E. nitens.
Overall product quality was good when it is considered that the drying schedule that was applied was designed to express differences in drying performance between trees and families. Decay and kino did not lead to significant down-grading of boards, and despite the absence of pruning, over half of the boards were graded as select grade or better with respect to knots, and only 2% were rejects. Had a more conservative (lower temperature) schedule been applied in the early stages of drying it is likely that cupping would not have been as severe and hence product quality would have been much better. In future research of this type it will be valuable to reassess the drying methods that are employed and model the drying systems financially to determine the optimum drying methodology. There will be a compromise between the higher cost, in inventory and associated costs such as insurance, of a milder, longer regime, and the drying degrade, leading to lower product value, of an increasing proportion of boards as the severity of the schedule is increased.

It should be kept in mind that the central board in the cant of five boards from each log was discarded, and this board would typically be rejected because of defects such as unrecoverable surface checking associated with the central pith. The extent to which the logs studied are representative of the entire stand must also be considered. As noted, the logs sawn were all “second best” logs from individual 4-tree family plots, which were thinned to the best two trees per plot at age 4 years, but logs with serious visible defects were not included in the study. The consequence of these two opposing sampling constraints is that the board grades from the sampled logs were probably close to the overall mean of grades that would be obtained from the thinned stand.

The rapid growth rate achieved in this trial (mean height of 26.4 m in just under ten years) demonstrates the excellent growth potential of the species in suitable environments. The mean ratio of height in metres to Dbh in cm of the 40 sawn logs exceeded 100 (mean height 29.6 m, mean Dbh 25.3 cm, mean ratio 1.17; Table 3). In comparison with the *E. globulus* trees subjected to systematic studies of tension wood occurrence by Washusen and Ilic (2001) and Washusen et al. (2004, 2005) this ratio is relatively high. In their studies tension wood was found to be more prevalent in trees that had higher aspect ratios. Assuming that tension wood is also common in *E. dunnii*, a sawlog silvicultural regime with early thinning to lower stocking would produce lower height to Dbh ratios, and consequently less potential for tension wood formation. Pruning would reduce defects associated with knots. Thus, there are good prospects for solid-wood production from *E. dunnii* plantations, including production systems based around sawing small-diameter unpruned logs of the size studied here. However, it is important to note that in a parallel trial of the same 219 *E. dunnii* families at Megan, a site some 30 km distant with an elevation of 700 m, growth was much slower and wood properties were significantly different, with mean basic density 35 kg m\(^{-3}\) lower and a screened pulp yield of 50.1%, compared to 53.3% for Boambee (Henson and Vanclay 2004). The environment of Megan is more typical of the site type where *E. dunnii* will be planted.

The indication of significant between-family differences in the basal cupping of the boards sawn from the 40 trees, and significant differences between trees for several other board traits including end-splitting and spring, is an important finding in this trial and suggests the potential to genetically improve *E. dunnii* for solid wood products. Such improvement would be realised through the achievement lower levels of drying degrade under accelerated drying schedules, as applied in this study, using a plantation resource bred for reduced cupping. However, it must be kept in mind that the sample size of a total of 40 trees from 27 families, and only 2-4 boards from each log, is very small for the detection of significant genetic
differences, and too small the estimation of heritabilities. Estimation of heritabilities and additive genetic variances of board traits such as cupping, spring and end-splitting, to predict genetic gain from breeding and deployment strategies, would require larger sample sizes: sawing say 3 trees per family from at least 30-40 families should be sufficient for this purpose. Henson et al. (2004) obtained high heritabilities (greater than 0.5) for tangential and radial shrinkage and modulus of rupture measured on boards cut from 179 short butt-logs from 47 families in the trial, moderate (0.2 -0.3) heritabilities for Janka hardness and modulus of elasticity, but low, non-significant heritabilities for internal checking and collapse.

Core basic density and the core tangential shrinkage properties studied appear to of limited value for predicting board degrade associated with processing defects when efficient processing strategies are applied. None of the measured core properties predicted cupping, the most important board defect. There was little surface and internal checking, which has been suggested as being likely to be linked to core shrinkage properties in past trials (Kube and Raymond 2005). Also, particularly for the upper pseudocores, there were very few bands of pronounced shrinkage such as might be associated with major reduction in board quality. The value of assessing tangential shrinkage in cores as a means of improving processing performance in E. dunnii should therefore be questioned, although it should be noted that Henson et al. (2004) found phenotypic and genetic correlations of 0.48 and 0.99 respectively between core tangential shrinkage and board tangential shrinkage, so core shrinkage could be of value in predicting excessive shrinkage leading to product under-sizing. Tangential shrinkage of cores might be a better predictor of board defects in more check-prone species such as E. nitens (Kube and Raymond 2005). The ratio of tangential to radial wood shrinkage, and changes in the proportion of tension wood as indicated by changes in crystallite width, might be better predictors of economically significant board defects in E. dunnii. It would be worthwhile to examine microscopic sections of those regions of the pseudocores where matched SilviScan readings exceeded 3.6 nm, to determine whether crystallite width is a reliable predictor of tension wood occurrence, as was found for E. globulus by Washusen and Ilic (2001).

We hoped to get a match between pseudocore tangential shrinkage properties and adjacent board defects at the individual board level, through the use of image scans of the cores (Appendix 2), and mapping board positions to the matching sections of the core. In practice, preparing image scans of cores was time-consuming and could not be considered a “low-cost” assessment option. Measurement of maximal shrinkage, or shrinkage at marked points along the core or pseudocore, using digital callipers with electronic data capture, would be quicker and appears a more practical option if the technique were to be adopted for routine assessment.

It may have been possible to obtain a clearer link between the studied core shrinkage properties and board properties by sampling only logs that were at the extremes of the range of core shrinkage. We did not attempt such a “forcing” of the relationships, and took a representative sample of logs, because we wished to apply any core-board relationships to the entire breeding population under study, so as to make inferences about the potential for genetic improvement through selection and breeding. Nonetheless, working with a sample of the extremes might be a realistic strategy for trying to identify trees likely to produce logs with defects that exceed defined “economic limits”. A larger sample size (more trees sawn) may also have helped to establish significant relationships between core and board traits, although it is clear from Figures 8 and 9 that such relationships will be imprecise at best.
RECOMMENDATIONS AND CONCLUSIONS

More research, including financial modelling, needs to be done to evaluate the optimum drying schedules for plantation-grown *E. dunnii*. Optimum regimes will balance the higher cost of less severe, longer drying regimes against their expected lower downgrading of product quality through drying degrade, compared with the rapid drying schedule used here.

In future studies that aim to predict log quality and value from core properties, it is recommended that both tangential and radial shrinkage (as opposed to tangential shrinkage alone) be measured in wood samples prepared from cores, as their ratio is likely to be linked to drying stresses and the development of associated defects such as cupping which were severe in this study.

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REFERENCES


### GLOSSARY

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Backsawing</td>
<td>Backsawn boards are sawn such that the growth rings meet the wide face of the board at an angle of less than 45°.</td>
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<tr>
<td>Bow</td>
<td>Distortion of a sawn board through bending along its length in the tangential plane (for backsawn boards)</td>
</tr>
<tr>
<td>Checking</td>
<td>Separation of the wood cells along the grain forming a crack or fissure not extending through the piece from one side to the other. Checking may be surface, or internal, the latter only evident on cross-sectioning or re-sizing the board.</td>
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<tr>
<td>Collapse</td>
<td>Flattening or buckling of the wood cells during drying, manifested in shrinkage that is recoverable on steam reconditioning</td>
</tr>
<tr>
<td>Cup</td>
<td>Distortion of a board through bending across its width in the cross section of the piece</td>
</tr>
<tr>
<td>Dbh</td>
<td>Diameter at breast height (1.3 m), over bark in this report</td>
</tr>
<tr>
<td>Heritability</td>
<td>The proportion of total variation in a trait which is due to genetic effects</td>
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<tr>
<td>Kino</td>
<td>Red-black solids or viscous liquids found in cavities in the wood.</td>
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<tr>
<td>Microfibril angle</td>
<td>The angle to the vertical of the cellulose microfibrils in the S2 layer of the cell wall.</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>Reduction in dimensions of a piece of wood due to decreased moisture content below the fibre saturation point, expressed as a percentage of the green dimension.</td>
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<tr>
<td>Spring</td>
<td>Longitudinal bending of a sawn board towards the bark, along its length</td>
</tr>
<tr>
<td>Wane</td>
<td>Presence of the original underbark surface on any face or edge of a piece of timber</td>
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APPENDIX 1

CSIRO Hardwood Appearance Product Assessment Criteria
Modified June 2002

Scope
Specifications apply to sawn eucalypt products for appearance applications and can be applied to dressed or dry rough sawn products.

Grade Descriptions

(a) Polishing grade:
The wood will be graded in its entirety, on the worst defect and will be free of decay, stain, kino pockets, knots, borer and termite attack, end splits, wane and Lyctus-susceptable sapwood. The following specifications shall apply:

(i) Product orientation - Back-sawn products are acceptable only if graded dry, in which case, the prescribed allowance for checks will not be exceeded.
(ii) Product sizing - Minimum dimensions for dry rough-sawn products must be 3 mm greater than final dressed size and allowance must be made for shrinkage when grading green wood. Green sizing over a parcel must not vary by more than 2 mm.
(iv) Moisture content - Average moisture content of 10%, with all pieces within the range of 7% to 12%.

In addition, the following imperfections will be allowed:
(v) Tight kino veins - Up to 1 mm in width and no greater than 1.5 mm on the graded surface. No greater than 600 mm in length for every square metre of surface and individually not exceeding 200 mm.
(vi) Spring - 8 mm in 3 metres length.
(vii) Bow - 10 mm in 3 metres length.
(viii) Surface checks - Of less than 1 mm in width and 2 mm depth, in aggregate length not more than 250 mm in 1 square metre and no more than one surface check in any 0.04 square metre (400 x 100 mm) area.
(ix) Internal checks - As appearing on freshly docked ends. Must be confined to the middle of the thickness of the piece, not exceeding 1 mm in width and not exceeding 4 mm radially or extending through the late-wood. No more than 1 on any cross section less than 0.005 square metre (100 x 50 mm) area, or 2 in any larger cross-section.
(x) Sloping grain - Not exceeding 1 in 20.

(c) Select grade:
The wood will be graded on the best face and both edges, which must be free of decay, borer holes, kino pockets, termite galleries, end splits, wane and Lyctus-susceptable sapwood. The back will be graded to cover grade (see below) except for the exceptions listed below. The following specifications shall apply:

(i) Product orientation - Back-sawn products are acceptable but must be sawn so that all wood is at least 60 mm or half product width, or whichever is the greatest from the pith.
(ii) Product sizing - Minimum dimensions for dry rough-sawn products must be 3 mm greater than final dressed product and due allowance made for shrinkage when grading green wood. Green sizing over a parcel must not vary by more than 3 mm.
(iv) Moisture content - Average moisture content of 10%, with no more than 10% of pieces being within the range of 12% to 15%, all remaining pieces within the range of 7% to 12%.

In addition, the following imperfections will be allowed:
(v) Tight kino veins - Up to 1 mm in width and no greater than 2.5 mm on the graded surface. No greater than 1.5 metre in length for every square metre of surface.
(vi) Light stain only
(vii) Spring - 10 mm in 3 metres length.
(viii) Bow - 25 mm in 3 metres length, except for lining boards and strip flooring sizes, when up to 40 mm is allowable.
(ix) Wane and Lyctus susceptible sapwood - On lining boards and strip flooring only. On the opposite face to that graded, for 25% of the width and lower edge only, for a maximum of 25% of the sawn face.
(x) Knots - Tight green knots only, less than 20% of product width and no more than three per square metre of surface area.
(xi) Surface checks - Of less than 1 mm in width and 3 mm depth, in aggregate length not more than 1 metre in 1 square metre of surface area.
(xii) Internal checks - As appearing on freshly docked ends, not exceeding 1 mm in width and not extending through the late-wood. No more than 3 in 0.005 square metre (100 x 50 mm) area.
(xiii) Holes - No more than 2 mm in diameter and no more than 10 per square metre of surface area.
(xiv) Sloping grain - Not exceeding 1 in 15.
(d) Standard grade:
The wood will be graded on the best face, which must be free of decay, borer holes of more than 5 mm diameter, kino pockets, termite attack, end splits, wane and *Lyctus*-susceptable sapwood. The following specifications shall apply:

(i) **Product orientation** - Back-sawn products are acceptable but must be sawn so that all wood is at least 60 mm or half product width, or whichever is the greatest from the heart (or pith).

(ii) **Product sizing** - Minimum dimensions for dry rough-sawn products must be 3 mm greater than final dressed size and allowance must be made for shrinkage when grading green wood. Green sizing over a parcel must not vary by more than 3 mm.

(iv) **Moisture content** - Average moisture content of 12%, within the range of 9% to 15%.

In addition, the following imperfections will be allowed:

(v) **Tight kino veins** - Up to 1.5 mm in width. No greater than 3 metre in length for every square metre of surface.

(vi) **Light stain only**

(vii) **Spring** - 10 mm in 3 metres length.

(viii) **Bow** - 25 mm in 3 metres length, except for lining boards and strip flooring sizes, where up to 40 mm is allowable.

(ix) **Wane and Lyctus susceptible sapwood** - On the opposite face to that graded, for 25% of the width and lower edge only, for a maximum of 25% of the sawn face.

(x) **Knots** - Tight green knots and epicormic shoots (burls) only, no greater than 30% of product width and no more than six per square metre of surface area.

(xi) **Surface checks** - Of less than 1 mm in width and 5 mm depth, in aggregate length not more than 2 metre in 1 square metre of surface area.

(xii) **Internal checks** - As appearing on freshly docked ends, not exceeding 1 mm in width. No more than 6 in 0.005 square metre (100 x 50 mm) area.

(xiii) **Holes** - Up to 2 mm in diameter and no more than 20 per square metre of surface area. From 2 mm to 5 mm, no more than 5 per square metre of surface area. In combination, one larger hole equates to four smaller holes.

(xiv) **Sloping grain** - Not exceeding 1 in 10.

(e) Utility grade:
The sawn product will be 2.4 metre length or longer and graded on the best face, which must be free of decay, holes greater than 8 mm diameter, kino pockets, termite galleries, wane and *Lyctus*-susceptable sapwood. Back-sawn products are allowable but must be sawn so that the wood is a minimum distance of 50 mm from the pith. Average moisture content of 12%, with all pieces within the range of 9% to 15%.

In addition, the following imperfections will be allowed:

(i) **Kino veins** - Tight kino veins up to 1.5 mm in width unlimited. Wider, but tight kino veins, not exceeding the length of the piece.

(ii) **Stain** - Brown

(iii) **Spring** - 10 mm in 3 metres length.

(iv) **Bow** - 40 mm in 3 metres length.

(v) **Wane and Lyctus susceptible sapwood** - On the opposite face to that graded, for 25% of the width and lower edge only.

(vi) **Knots** - Tight green knots and epicormic shoots (burls) only, no greater than 40% of product width. Partially dead knot (tight on at least 50% of the knot perimeter) up to 30% of product width.

(vii) **Surface checks** - Of less than 1 mm in width unlimited. Wider checks to 2 mm in width, in aggregate length not more than 1 metre in 1 square metre of surface area.

(viii) **Internal checks** - As appearing on freshly docked ends. Of less than 1 mm - unlimited. Wider checks to 2 mm - no more than 3 per 0.005 square metre (100 x 50 mm) area.

(ix) **Holes** - Up to 2 mm in diameter unlimited. Larger holes to 8 mm diameter - no more than 10 per square metre.

(x) **Sloping grain** - Not exceeding 1 in 10

(h) Cover grade:
The sawn product will be 2.4 metre length or longer and graded on the worst defect or combination of defects on a piece, which must be free of termite attack, decay, wane and *Lyctus*-susceptable sapwood. Back-sawn products are allowed but must be sawn so that the wood is a minimum distance of 50 mm from the pith. Average moisture content of 10%, with all pieces within the range of 7% to 12%.

In addition, the following imperfections will be allowed:

(i) **Kino veins** - Tight kino veins unlimited.

(ii) **Stain** - Brown

(iii) **Spring** - 10 mm in 3 metres length.

(iv) **Bow** - 10 mm in 3 metres length.

(v) **Knots** - Tight green knots and epicormic shoots (burls) only, no greater than 40% of product width. Partially dead knot (tight on at least 50% of the knot perimeter) up to 30% of product width.

(vi) **Checks** - Both internal and surface, individual checks not exceeding the lesser of half of piece thickness or two growth rings, or wider than 3 mm.

(vii) **Holes** - Up to 8 mm in diameter unlimited. Up to 20 mm, no more than 10 per square metre.

(x) **Sloping grain** - Not exceeding 1 in 10
APPENDIX 2

Typical scans (actual size, i.e. scale is 1:1) of basal and upper pseudocores after drying at 70°C, and before reconditioning. Cores were constrained in aluminium channelling to prevent distortion during drying.
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