Stiffness and Density Analysis of Rotary Veneer Recovered from Six Species of Australian Plantation Hardwoods

Robert L. McGavin,[a,b,]* Henri Bailleres,[b] Joh Fehrmann,[b] and Barbara Ozarska [a]

Commercial interest in Australian hardwood plantations is increasing. The timber industry is investigating alternative supplies of forest resources, and the plantation growing industry is eager to explore alternative markets to maximize financial returns. Identifying suitable processing strategies and high-value products that suit young, plantation-grown hardwoods have proven challenging; however, recent veneer processing trials using simple veneer technology have demonstrated more acceptable recoveries of marketable products. The recovered veneers have visual qualities that are suitable for structurally-based products; however, the mechanical properties of the veneer are largely unknown. Veneers resulting from processing trials of six commercially important Australian hardwood species were used to determine key wood properties (*i.e.,* density, dynamic modulus of elasticity (MoE), and specific MoE). The study revealed that a wide variation of properties existed between species and also within species. Simple mathematical modeling, using sigmoidal curves, was demonstrated to be an effective method to model the evolution of key wood properties across the billet radius and along the resulting veneer ribbon with benefits for tree breeders and processors.

Keywords: Eucalyptus; Veneer; Hardwood; Plantation; Processing; Quality; Structural; Density; Modulus of elasticity

*Contact information: a: University of Melbourne, Department of Ecosystem and Forest Sciences, 500 Yarra Boulevard, Richmond, Victoria 3121 Australia; b: Queensland Department of Agriculture and Fisheries, Horticulture and Forestry Science, Salisbury Research Facility, 50 Evans Road, Salisbury, Queensland 4107 Australia; *Corresponding author: robbie.mcgavin@daf.qld.gov.au*

INTRODUCTION

Forest resources in Australia, which are available to the commercial timber industry, are undergoing a substantial change. Gavran (2013) reports that over two million hectares of plantation forestry exist in Australia, of which about one million hectares are hardwood species. While the industry's softwood sector has become well established over recent decades by relying on a plantation resource, the hardwood sector remains largely dependent on native forests for log supply, especially to provide high-value wood products. While a substantial area of hardwood plantations exists, the majority of the plantations have only been established in recent decades and only recently started to become available to the timber industry for end-uses other than pulpwood.

With a greater proportion of plantation-grown forest becoming available to the wood processing sector, combined with significant areas of native hardwood forests across Australia being progressively withdrawn from commercial harvesting and managed for conservation purposes, interest in hardwood plantations by Australia's hardwood sector is rapidly increasing. In addition, plantation growers are continuously seeking processing streams and end-uses that can provide the highest return from the plantations.

Of the one million hectare hardwood estate, around 84% has been established for pulpwood production (Gavran 2013), meaning that the majority of the estate contains a mix of species and forest and wood qualities that are most likely not optimal for targeting higher-value products. Some small areas of plantations have been established and managed with a high-value product focus. For example, Wood *et al.* (2009) reported approximately 26,000 hectares of plantations, principally located in Tasmania, which have been thinned, pruned, and managed for high-value end-uses.

With rapidly growing interest in hardwood plantations by the Australian timber industry, and growers' interest in maximising the value of their plantations, many studies have investigated solid wood processing options (*i.e.,* sawmilling) for the plantation hardwood resource. As summarised by McGavin *et al.* (2014a), despite the varied approaches, mainly based on alternative technologies targeting sawn timber products, many challenges remain, resulting in excessively low recovery of marketable products and unprofitable processes.

The processing of Australian grown plantation hardwoods into veneer using relatively new small-scale spindleless veneer lathe technology has been demonstrated in research trials to produce product recoveries that are much more favourable when compared to solid wood processing techniques (McGavin *et al.* 2014a,b; 2015). While the technology approach is not necessarily new, recent advancements in design allow the technology to be well suited to small diameter plantation forest resources. The advancements have been quickly adopted through many Asian countries, including China and Vietnam, for successful veneer production from very small diameter hardwood billets. Arnold *et al.* (2013) reported well over 5000 small-scale veneer mills operating in China.

While the veneer recoveries reported by McGavin *et al.* (2014a,b) were high (net recoveries up to 58% of log volume), the grade recoveries were dominated by D-grade veneers (lowest visual quality) when graded to Australian and New Zealand Standard AS/NZS 2269.0:2012 (Standards Australia 2012).

With such a dominance of low appearance qualities, the veneers are potentially more suited to structural products where higher appearance traits are less relevant. However, to be acceptable in this market, the veneer is required to meet certain mechanical properties requirements (*e.g.,* stiffness). In addition, an understanding of the variation in mechanical properties from within a species, between trees and billets and within a billet, is critical in determining the optimal processing strategy, grading and quality segregation systems, and final target products.

Within-tree radial variation (pith to bark) of wood characteristics is described by Larson (1967) (in Zobel and van Buijtenen 1989), as being very large and more variable than between trees growing on the same or on different sites. Several equation types have been reported in previous studies to describe ontogenetic variation for tree characteristics, largely on the basis of the best fit rather than on clear biological mechanisms (*e.g.,* Koch 1972; Downs *et al.* 1997; Zobel and Sprague 1998). Alternatively, West *et al.* (2001) derived a general quantitative model based on fundamental principles for the allocation of metabolic energy between the maintenance of existing tissue and the production of new biomass. Thus, they predicted the parameters governing growth curves from basic cellular properties and derived a universal family of curves that describes the growth of many diverse species. These curves represent a classical sigmoidal shape. The model provides the basis for deriving allometric relationships for growth rates and time. Specific properties related to biomass increase, such as density or stiffness, follow the same pattern. Indeed, the specific wood density is a simple measure of the total dry mass per unit volume of wood. It is also closely related to basic wood mechanical properties such as stiffness (or Modulus of Elasticity, MoE) (Kollmann and Cote 1968; Koch 1972). While not necessarily recognized, in most experimental studies wood mechanical property trajectories have the characteristic sigmoidal shape that is observed empirically (*e.g.*, Zobel and Van Buijtenen 1989; Zobel and Sprague 1998). Bailleres *et al.* (2005) reported the use of sigmoidal profiles as an effective method to describe some select key wood properties in planted *Eucalyptus* species.

The objective of this study was to describe, at a species level, the density and modulus of elasticity (MoE) of veneer recovered from six hardwood plantation species based on global variation from pith to bark. Sigmoidal curves were used to describe these characteristics. In addition, the trial results were to be in a format that was recognisable and directly relevant to the commercial processing industry. Veneer density and MoE are key in determining the suitability of veneer for structural veneer-based engineered wood products. The resulting analysis provides guidance on the quality of the current plantation resources for structural product end-uses, plantation management, product development programs, and marketing strategies.

EXPERIMENTAL

Materials

Veneers were sourced from processing studies conducted on billets harvested from Australian commercial plantation stands, representing the average resource available for industry to access now and in the immediate future (McGavin *et al.* 2014a). Six of the major commercially important Australian hardwood species were included and ranged from traditional pulp to high quality solid wood species. They include *Corymbia citriodora* subspecies, *variegata* (spotted gum), *Eucalyptus cloeziana* (Gympie messmate), *Eucalyptus dunnii* (Dunn's white gum), *Eucalyptus pellita* (red mahogany), *Eucalyptus nitens* (shining gum), and *Eucalyptus globulus* (southern blue gum) (Table 1). Plantation ages ranged between 10 and 16 years for all species except *Eucalyptus nitens*, which was between 20 and 21 years old. These plantations were older by comparison; however, they are reflective of the *E. nitens* plantation resource immediately available to the wood processing sector.

Processing was undertaken using an OMECO spindleless veneer lathe, model TR4 (OMECO, Curitiba, Estado de Paraná, Brazil). The lathe is capable of processing billets with a maximum length of 1350 mm and maximum log diameter of 400 mm. The minimum diameter of the peeler core was 45 mm. A very small number of *E. nitens* billets were too large (> 400 mm diameter) to process on the spindleless lathe; these billets were rounded and/or partially peeled using a conventional spindled lathe before the peeling was completed on the spindleless lathe. For this study, the nominal dried veneer thicknesses were 2.4, 2.5, or 3.0 mm, depending on species and according to the thickness range mostly used by the Australian industry for structural plywood production.

The resulting veneer ribbon was sequentially clipped to target 1400 mm maximum width sheets. This target sheet size was chosen to provide 1200 mm dried and trimmed veneer sheets as per standard industry practice. These veneers sheets were used for detailed visual grade quality analyses as reported by McGavin *et al.* (2014b; 2015). More detailed description of the methodology regarding plantation selection, billet preparations, and processing, is described by McGavin *et al*. (2014a).

Table 1 provides a description for each species, age, plantation location, number, the diameter at breast height over bark (DBHOB) of the trees sampled, and the number of billets and sampling strips included in the study.

Table 1. Plantation Trial Material

Species	Age (years)	Plantation Location	Number of Trees	Average DBHOB * (cm)	Number of Billets	Number of Sampling Strips
Corymbia citriodora subsp. *variegata*	10–12	Northern New South Wales and South-east Queensland	80	20.6 (2.5)	215	713
Eucalyptus cloeziana	12–15	South-east Queensland	55	31.9 (6.3)	223	967
Eucalyptus dunnii	11	Northern New South Wales	60	22.9 (3.5)	148	500
Eucalyptus pellita	13	North Queensland	38	28.1 (4.3)	130	1013
Eucalyptus nitens	20–22	Tasmania	41	34.0 (7.4)	82	972
Eucalyptus globulus	13–16	Victoria	60	30.6 (3.7)	120	1187
* Standard deviation is presented in parentheses.						

Between the clipped veneer sheets, sampling strips for density and dynamic MoE measurements were removed. Sampling in this manner ensured representation from billets in line with veneer sheet production when processed by the commercial processing industry.

The sampling strips measured 150 mm (parallel to the grain) by 1300 mm (the length of the veneer sheet) and aimed to be representative of the adjacent veneer sheets (Fig. 1). Therefore, any defects that were present were included within the sampling strip to ensure a realistic representation of the veneer qualities (*i.e.*, sampling strips were not biased towards clear of defect veneer). The sampling strips were air-dried to 12% MC, prior to density and dynamic MoE measurement.

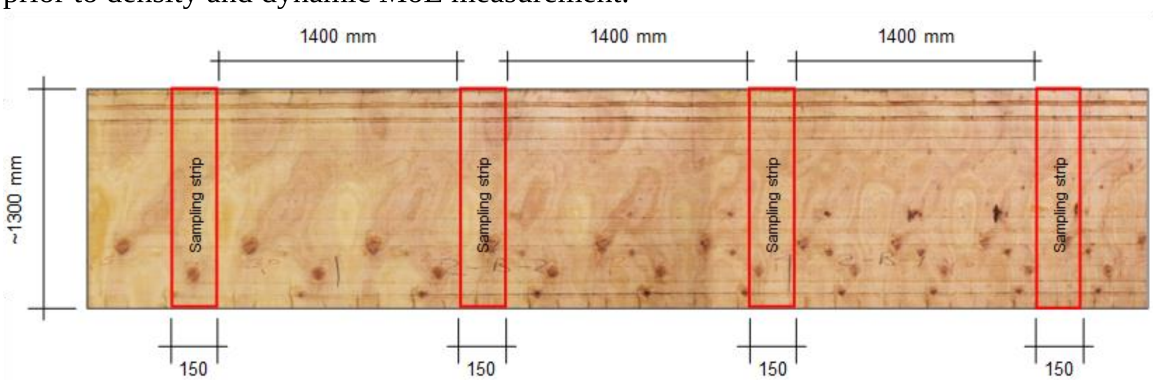

Fig. 1. Schematic demonstrating clipping strategy and sample strip origin

Methods

Sample strip dimensions (length, width, and thickness) and weight were measured, allowing veneer density to be calculated. Veneer MoE measurements were followed using an acoustic natural-vibration method as described by Brancheriau and Bailleres (2002).

Sample strips were positioned on elastic supports so that the longitudinal propagation of vibration was as free as possible and could be induced by a simple percussion on one end of the sample, in the grain direction (Fig. 2). At the other end, a Lavalier type microphone recorded the vibrations before transmitting the signal via an anti-aliasing filter (low-pass) to an acquisition card, which included an analog-to-digital converter to provide a digitized signal.

A Fast Fourier Transform processed the signal to convert the information from the time to the frequency domain. The mathematical processing of selected frequencies was undertaken using BING (Beam Identification using Non-destructive Grading) software in combination with the geometrical characteristics and the weight of the specimen, to provide the dynamic MoE, among other specific mechanical characteristics (CIRAD 2009; Pico n.d).

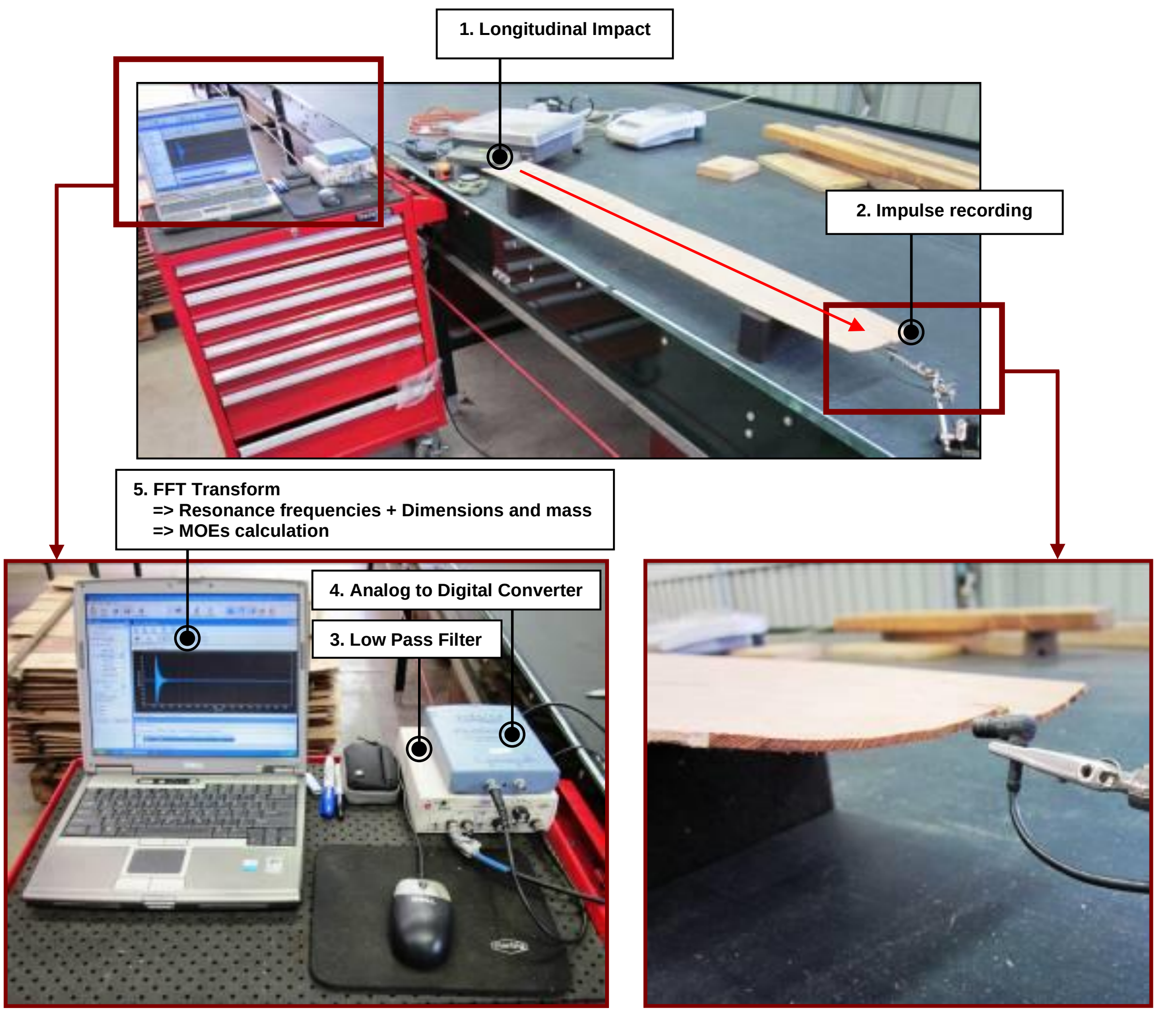

Fig. 2. Experimental setup for the acoustic measurement of veneer MoE

Specific MoE is a materials property consisting of the elastic modulus per mass density of a material (Manufacturing Terms, n.d). It is also known as the stiffness to weight ratio or specific stiffness. Specific MoE is an effective property to compare materials during structure design and materials specification stages, especially where high MoE requirements exist and minimum structural weight is being targeted. Specific MoE comparison is useful when the main design constraint is physical deformation before strength (known as "stiffness-driven"). Many common structural components are stiffness-driven because of their primary usage, such as bridge decks and floors.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics software, version 23 (IBM, USA). Normality of the data distribution was checked using Kolmogorov–Smirnov and Shapiro–Wilk tests. The assumption of homogeneity of variances was tested using Levene's test of equality of variances. When data normality or equality of error variances (Levene's test) was not established, the Kruskal–Wallis non-parametric H test was used to establish significant differences between species. The level of significance was set at 5% ($P < 0.05$).

Subsequently, stepwise step-down comparisons were performed using Dunn's (1964) procedure with a Bonferroni correction for multiple comparisons.

Data fitting

A sigmoidal model was applied for non-linear fitting of the density and MoE data using TableCurve 2D version 5.01 (Systat Software, USA). The following Boltzmann four-parametric sigmoid function was fitted to the data (Eq. 1),

$$f(x) = a_0 + \frac{(a_1 - a_0)}{1 + e^{\frac{(x - a_2)}{a_3}}} \tag{1}$$

where a_0 is the maximum asymptote. This can be thought of as the value for infinite x value or final value. The quantity a_1 is the minimum asymptote, which can be thought of as the response value at x=0 or initial value; a_2 is the total variation centre (inflexion point); and a_3 is a time constant. The span is abs(a_1-a_0).

The Boltzmann function displays perfect symmetry for the sigmoidal curve around the inflection point. This approach has the advantage of describing the parameter variations considered solely in terms of only four parameters, the values of which can be determined by fitting experimentally measured density and MoE data. This approach provides a simple way to describe the variation from scattered datasets that result from measurements on specimens, which include natural features (knots, grain deviation, resin pocket, decay, reaction wood, *etc.*), as observed in the industrial process.

Curve-fitting algorithms use a reiterative process that systematically changes the value of each variable such that correlation with the experimental data is maximized, a process that is repeated until a specified tolerance is satisfied. The Levenberg-Marquardt non-linear curve-fitting algorithm was used throughout, with convergence to nine significant figures after a maximum of 4,000 iterations.

RESULTS AND DISCUSSION

The six species presented obvious differences in terms of basic statistics for density, dynamic MoE, and specific MoE, as displayed in Table 2 and in Figs. 3 to 5. The distribution of density values for the six species (Fig. 3) indicates that there was a clear trend with the three sub-tropical/tropical species (*E. cloeziana, C. citriodora*, and *E. pellita*) possessing higher densities compared with the more temperate species (*E. globulus*, *E. nitens*, and *E. dunnii*). This is despite the relatively young age of the plantations sampled.

Table 2. Density, Dynamic MoE, and Specific MoE Summary Statistics

Species	Property	Sample Number	Mean		Std. Deviation
			Statistic	Std. Error	
Corymbia citriodora	Density (kg/m^3)	713	795	2.83	76
	MoE (MPa)	713	16,005	152	4053
	Specific MoE ([MPa]/[kg/m3])	713	20.1	0.166	4.4
Eucalyptus cloeziana	Density (kg/m^3)	962	805	3.1	96
	MoE (MPa)	962	16,177	134	4155
	Specific MoE ([MPa]/[kg/m3])	962	20.0	0.145	4.5
Eucalyptus dunnii	Density (kg/m^3)	500	607	2.94	66
	MoE (MPa)	500	12,304	161	3606
	Specific MoE ([MPa]/[kg/m3])	500	20.1	0.22	4.9
Eucalyptus pellita	Density (kg/m^3)	1,013	748	2.51	80
	MoE (MPa)	1,013	13,734	120	3804
	Specific MoE ([MPa]/[kg/m3])	1,013	18.3	0.138	4.4
Eucalyptus nitens	Density (kg/m^3)	972	608	2.55	79
	MoE (MPa)	972	14,520	121	3766
	Specific MoE ([MPa]/[kg/m3])	972	23.8	0.16	5.0
Eucalyptus globulus	Density (kg/m^3)	1,187	710	2.96	102
	MoE (MPa)	1,186	15,896	142	4904
	Specific MoE ([MPa]/[kg/m3])	1,186	22.2	0.162	5.6

Eucalyptus cloeziana achieved the highest average density at 805 kg/m^3, followed closely by *C. citriodora* with 795 kg/m^3. *Eucalyptus pellita* followed with 748 kg/m^3 and then *E. globulus* with 710 kg/m^3. *Eucalyptus nitens*, despite being from the oldest plantations, and *E. dunnii* had similar lowest mean densities of 608 kg/m^3 and 607 kg/m^3, respectively.

The contour of the density distributions was similar for all species with the exception of *E. globulus*, which displayed a noticeably wider variation and flatter distribution (Fig. 3). This observation was also supported by *E. globulus*, displaying the largest density standard deviation of 102 kg/m^3 (Table 2).

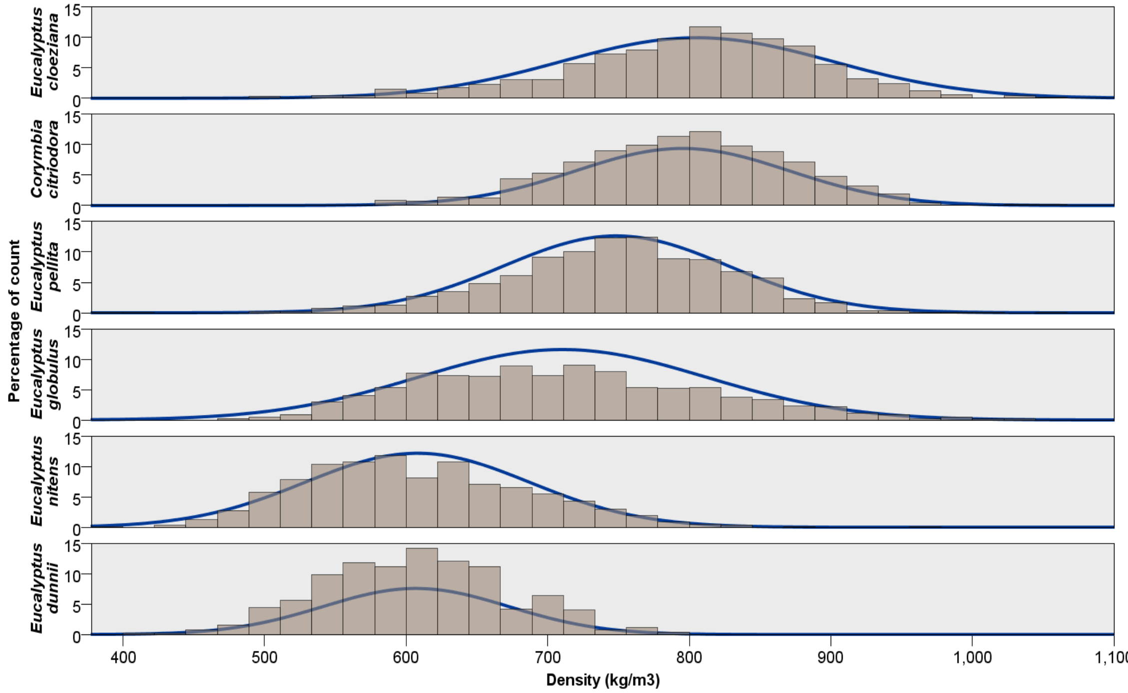

Fig. 3. Density histograms for each species with a normal distribution curve superimposed with the mean equal to the process mean and standard deviation equal to the process standard deviation

Similar to density, *E. cloeziana* ranked highest with an average MoE of 16,177 MPa, followed closely by *C. citriodora* with 16,005 MPa. *Eucalyptus globulus* followed with 15,896 MPa, *E. nitens* with 14,520 MPa, and then *E. pellita* with 13,734 MPa. *Eucalyptus dunnii* had the lowest mean MoE of 12,304 MPa (Fig. 4).

The MoE rankings were similar to the rankings for density with the exception of *E. pellita*, which dropped from a ranking of three to five. The occurrence of various defects in the *E. pellita* veneer including large knots, decay, and brittle heart, can explain this result, as these defects would have had minimal impact on density, but had negative consequences on MoE. This indicates that while density is often used to predict MoE, it cannot always be relied upon for estimating wood structural performances, especially when measured on industrial samples and not ‘clear wood’.

The relative distance between species was also reduced for MoE (Fig. 4) compared to the density results (Fig. 3). *Eucalyptus globulus*, similar to the density results, displayed wider variation and a flatter distribution than the other species.

Specific MoE values displayed a radical change of status compared to density and veneer MoE, with *E. nitens* being clearly upgraded. Despite this species having a low density (mean of 608 kg/m^3), the relatively modest MoE (mean of 14,520 MPa) resulted in the highest specific MoE of 23.8. *Eucalyptus globulus* ranked second with a mean of 22.2. *Eucalyptus cloeziana*, *C. citriodora*, and *E. dunnii* all resulted in similar mean specific MoE’s (20.0 to 20.1). *Eucalyptus pellita* ranked lowest with a mean of 18.3. This low result further demonstrates the impact of low MoE values, despite the comparably high density.

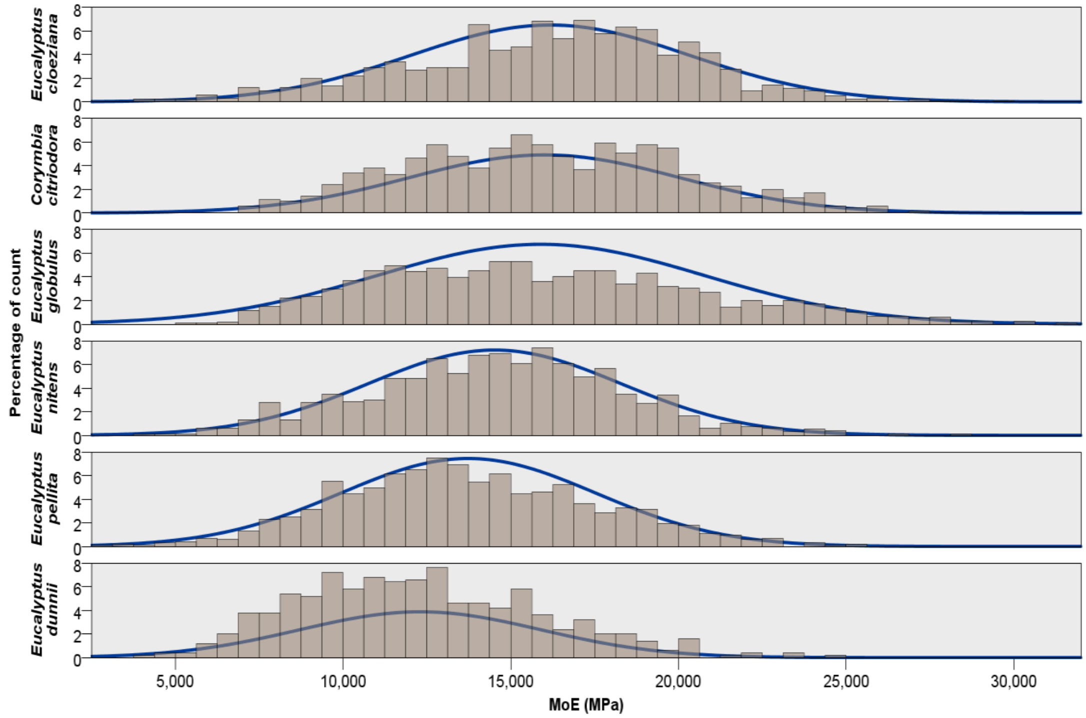

Fig. 4. MoE histograms for each species with a normal distribution curve superimposed with the mean equal to the process mean and standard deviation equal to the process standard deviation

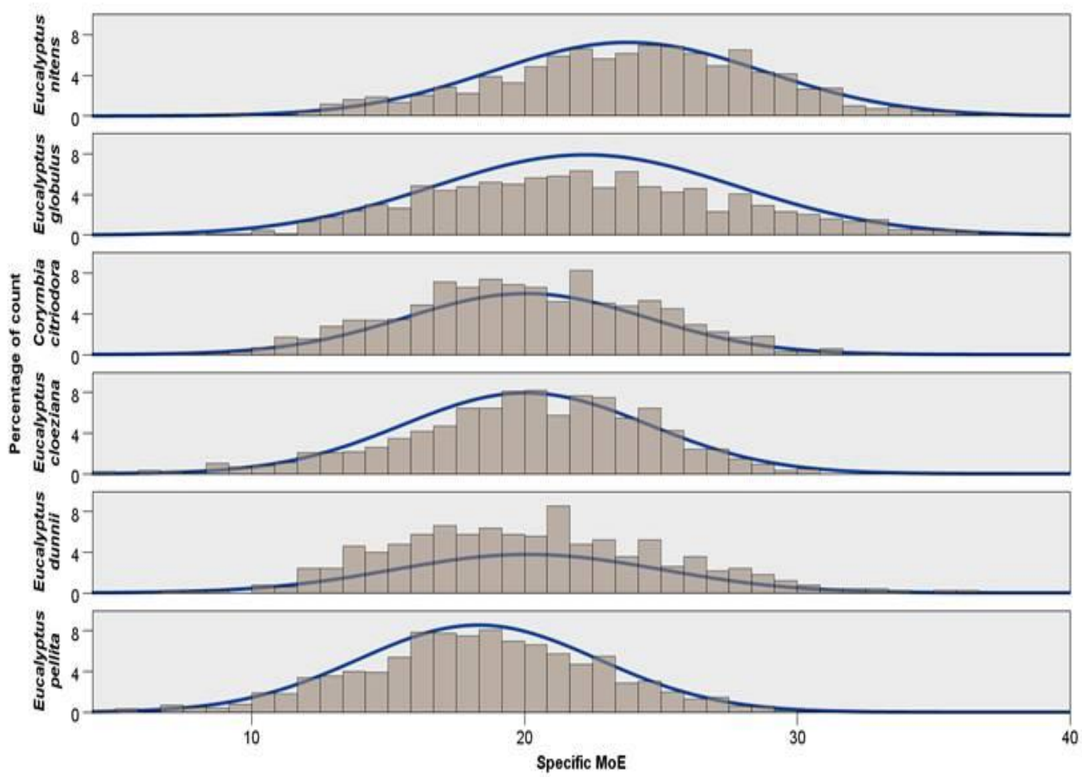

Fig. 5. Specific MoE histograms for each species with a normal distribution curve superimposed with the mean equal to the process mean and standard deviation equal to the process standard deviation

The specific MoE results indicate that from the trial species, *E. nitens* produced the most 'efficient' wood with the best stiffness to weight ratio, since globally the proportion of defects was comparable for all the species analyzed (McGavin *et al.* 2014b). This could be an attractive attribute for this species where stiffness properties are required along with a critical threshold on product weight. Despite *E. cloeziana* and *C. citriodora* achieving the highest average veneer MoE, these species dropped down the ranking order for specific MoE, as their high stiffness was offset by the high densities.

Table 3. Tests of Normality

Property	Species	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Density (kg/m^3)	*Corymbia citriodora*	.023	713	.200*	.997	713	.341
	Eucalyptus cloeziana	.058	962	.000	.964	962	.000
	Eucalyptus dunnii	.024	500	.200*	.997	500	.610
	Eucalyptus globulus	.038	1186	.000	.987	1186	.000
	Eucalyptus nitens	.048	972	.000	.986	972	.000
	Eucalyptus pellita	.030	1013	.029	.993	1013	.000
MoE (MPa)	*Corymbia citriodora*	.037	713	.024	.992	713	.001
	Eucalyptus cloeziana	.043	962	.000	.993	962	.000
	Eucalyptus dunnii	.044	500	.023	.985	500	.000
	Eucalyptus globulus	.049	1186	.000	.981	1186	.000
	Eucalyptus nitens	.020	972	.200*	.997	972	.040
	Eucalyptus pellita	.037	1013	.002	.995	1013	.002
Specific MoE	*Corymbia citriodora*	.028	713	.200*	.995	713	.031
	Eucalyptus cloeziana	.043	962	.000	.985	962	.000
	Eucalyptus dunnii	.047	500	.010	.992	500	.008
	Eucalyptus globulus	.029	1186	.017	.990	1186	.000
	Eucalyptus nitens	.027	972	.098	.995	972	.003
	Eucalyptus pellita	.022	1013	.200*	.998	1013	.135

* This is a lower bound of the true significance.
[a] Lilliefors Significance Correction

In order to test the above preliminary observations and examine trends for statistical significance, the data were first evaluated for outliers, normal distribution, and variance. Few outliers were identified relative to the total number of observations of each group (species). These were all considered valid and not a result of errors (*e.g.*, measurement error).

Two tests methods were conducted to determine whether the data were normally distributed (Table 3). The test methods included Kolmogorov-Smirnov and Shapiro-Wilk. The null hypothesis was rejected ($p < 0.05$) for most of the species, meaning that most of the data's distributions were not equivalent to a normal distribution.

A test of the homogeneity of variances was performed with one-way ANOVA analysis (Table 4). The assumption of homogeneity of variances was violated for all dependent variables, as assessed by Levene's test for equality of variances ($p < 0.05$). As a result of these statistical tests, non-parametric tests were pursued for the remainder of the analyses.

Table 4. Test of Homogeneity of Variances

	Levene Statistic	df1	df2	p-value
Density (kg/m^3)	33.628	5	5341	< .0005
MoE (MPa)	27.473	5	5345	< .0005
Specific MoE	18.711	5	5340	< .0005

From the inspection of the histograms (Figs. 3 to 5), the distributions are considered to be similar in shape for the three dependent variables examined (density, MoE, and specific MoE). A Kruskal-Wallis test was consequently conducted to determine whether there were differences in MoE, density, and specific MoE medians between species. Medians of MoE, density, and specific MoE were found to be statistically significantly different ($p < 0.0005$).

Subsequently, stepwise step-down comparisons were performed using Dunn's (1964) procedure with a Bonferroni correction for multiple comparisons for density, MoE, and specific MoE. This post hoc analysis revealed statistically significant differences in median density between most species, with the exception of *E. nitens* and *E. dunnii* (Table 5), statistical differences in median MoE between most species, with the exception of *E. globulus* and *C. citriodora* (Table 6), and significant differences in median specific MoE between the some species, but not between *E. dunnii*, *C. citriodora*, and *E. cloeziana* (Table 7).

Table 5. Homogeneous Subsets Based on Density Following Stepwise Step-Down Comparisons using Dunn's Procedure with a Bonferroni Correction for Multiple Comparisons

Species	Subset				
	1	2	3	4	5
Eucalyptus nitens	598.92				
Eucalyptus dunnii	606.91				
Eucalyptus globulus		706.00			
Eucalyptus pellita			751.75		
Corymbia citriodora				796.82	
Eucalyptus cloeziana					810.70

Homogeneous subsets are based on asymptotic significances.
The significance level is .05.
Each cell shows the sample median density (kg/m^3).

Table 6. Homogeneous Subsets based on Moe following Stepwise Step-Down Comparisons using Dunn's Procedure with a Bonferroni Correction for Multiple Comparisons

Species	Subset				
	1	2	3	4	5
Eucalyptus dunnii	11,993.5				
Eucalyptus pellita		13,434.5			
Eucalyptus nitens			14,598.0		
Eucalyptus globulus				15,416.0	
Corymbia citriodora				15,790.0	
Eucalyptus cloeziana					16,623.0

Homogeneous subsets are based on asymptotic significances. The significance level is .05.
The significance level is .05.
Each cell shows the sample median MoE (MPa).

Table 7. Homogeneous Subsets based on Specific Moe following Stepwise Step-Down Comparisons using Dunn's Procedure with a Bonferroni Correction for Multiple Comparisons

Species	Subset			
	1	2	3	4
Eucalyptus pellita	18.314			
Eucalyptus dunnii		19.961		
Corymbia citriodora		19.975		
Eucalyptus cloeziana		20.357		
Eucalyptus globulus			21.928	
Eucalyptus nitens				24.046

Homogeneous subsets are based on asymptotic significances.
The significance level is .05.
Each cell shows the sample median specific MoE.

To further test that the visual observations of the three dependent variables examined (density, MoE, and specific MoE) have a similar distribution shape (Fig. 3 to 5), an additional distribution comparison was conducted that compared the mean ranks of each distribution. The purpose was to determine whether the values in one species are lower or higher than the values in the other species. A Kruskal-Wallis H test confirmed that there were differences in density, MoE, and specific MoE between species ($p < 0.0005$).

Pairwise comparisons were performed using Dunn's (1964) procedure with a Bonferroni correction for multiple comparisons. This *post-hoc* analysis revealed statistically significant differences in mean score between most species across the three dependent variables. For density (Table 8), *E. dunnii* and *E. nitens* were not significantly different ($p > 0.05$); however, all other species were different. For MoE (Table 9), *E. globulus* and *C. citriodora*, and *C. citriodora* and *E. cloeziana* were not significantly different ($p > 0.05$); however, there were differences between the other species. For specific MoE (Table 10), there was more similarity between species with *E. dunnii*, *C. citriodora*, and *E. cloeziana* not being significantly different ($p > 0.05$).

The distribution analysis of mean rank showed a very similar result to the median analysis. For density and specific MoE, there was no difference. For MoE, the rank remained similar with the only difference being the lack of significant difference between *C. citriodora* and *E. cloeziana*, indicating that these species displayed a globally comparable MoE spread.

Table 8. Homogeneous Subsets based on Density

Species	Subset				
	1	2	3	4	5
Eucalyptus dunnii	a				
Eucalyptus nitens	a				
Eucalyptus globulus		b			
Eucalyptus pellita			c		
Corymbia citriodora				d	
Eucalyptus cloeziana					e

Table 9. Homogeneous Subsets Based on MoE

Species	Subset				
	1	2	3	4	5
Eucalyptus dunnii	a				
Eucalyptus pellita		b			
Eucalyptus nitens			c		
Eucalyptus globulus				d	
Corymbia citriodora				d	e
Eucalyptus cloeziana					e

Table 10. Homogeneous Subsets based on Specific MoE

Species	Subset			
	1	2	3	4
Eucalyptus pellita	a			
Eucalyptus dunnii		b		
Corymbia citriodora		b		
Eucalyptus cloeziana		b		
Eucalyptus globulus			c	
Eucalyptus nitens				d

To explore the dataset further and to provide an understanding of the evolution of density and MoE characteristics within species, sigmoid curves using Boltzmann four-parametric sigmoid function were applied to density and MoE. These were selected to describe the changes across the radius from pith to bark, and also along the veneer ribbon length. These are two different ways to analyse the data; the variation across the radius can be interpreted as the biological evolution of the characteristic observed as the tree formed new layers of wood over time, whereas the variation along the ribbon length relates directly to the products that a veneer processing mill will typically recover from rotary peeling. The difference between the two approaches is underlined by a simple mathematical transformation since at a first approximation, the ribbon length is linked to the square of the radius. Other characteristics, such as billet roundness and/or eccentricity, disturb the simple relationships between radius and ribbon position.

Table 11 shows the modelled parameters for density and MoE across the radius, while Fig. 6 provides a graphical display. There were some obvious differences between species. For density, the minimum values for *E. nitens*, *E. globulus*, *E. pellita*, and *E. dunnii* were in the same range (between 549 and 589 kg/m^3).

Table 11. Fitted Parameters for Density and MoE Across the Radius

	Parameters	*E. nitens*	*E. globulus*	*E. pellita*	*E. dunnii*	*C. citriodora*	*E. cloeziana*
Density (kg/m^3)	Minimum	562	589	587	549	707	643
	Maximum	634	784	758	640	833	822
	Inflexion position	83	73	33	59	39	50
	Rate at inflexion	2	3	8	2	2	6
	R^2	0.11	0.32	0.12	0.12	0.18	0.16
MoE (MPa)	Minimum	10655	10512	9379	7790	11090	10543
	Maximum	15698	18839	14328	13769	18291	17574
	Inflexion position	59	72	40	55	43	59
	Rate at inflexion	46	171	131	223	174	248
	R^2	0.18	0.31	0.07	0.18	0.28	0.23

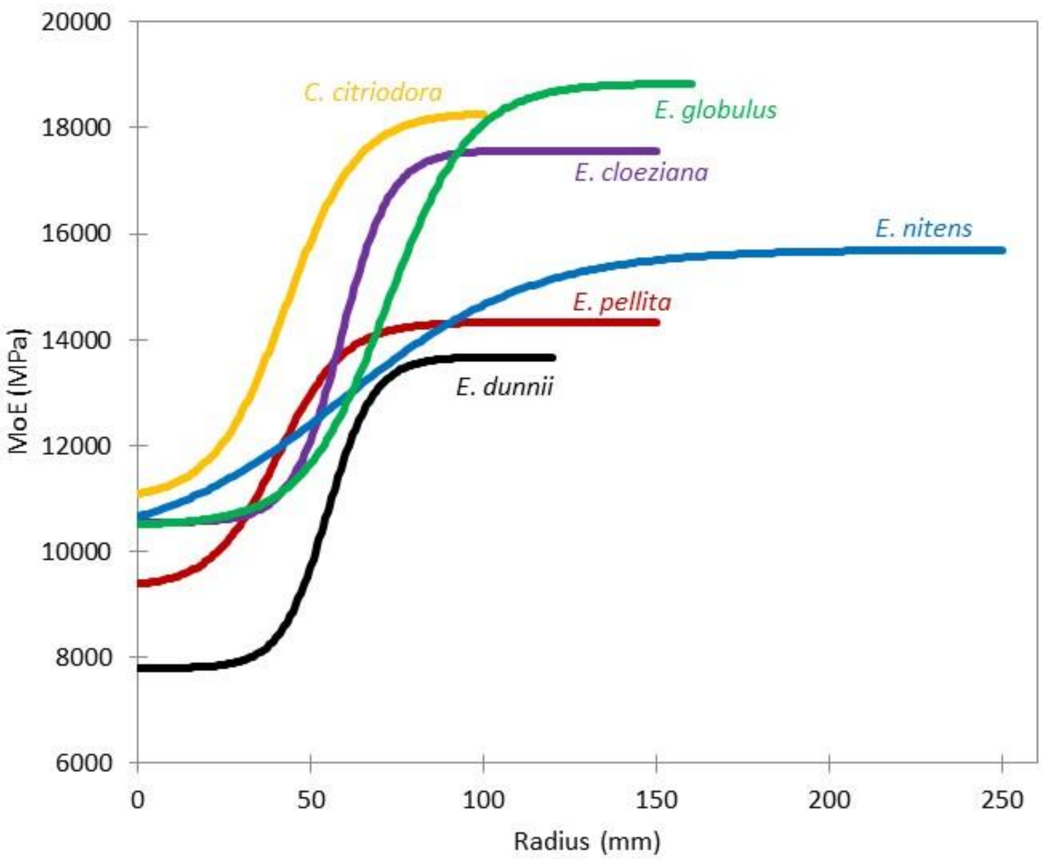

Fig. 6. Fitted MoE sigmoid curves across the radius for the six trialed species

Eucalyptus cloeziana had a higher starting point at 643 kg/m^3, while *C. citriodora* had the highest density starting point at 707 kg/m^3. The maximum density values showed more disparity, with *C. citriodora* and *E. cloeziana* producing comparable and the highest fitted values (833 and 822 kg/m^3 respectively). *Eucalyptus nitens* and *E. dunnii* both produced comparable and low fitted maximum densities of around 640 kg/m^3.

Fitted parameters for veneer MoE followed a slightly different trend to density. For minimum values, *E. dunnii* was much lower than the other species at 7,790 MPa. *Eucalyptus pellita* followed, with a minimum MoE of 9,379 MPa. *Eucalyptus globulus*, *E. cloeziana*, *E. nitens*, and *C. citrodora* all had comparable initial MoE values ranging from 10,512 to 11,090 MPa.

Despite the minimum values being relatively close across all species, the maximum MoE values displayed a much wider variation. Both *E. dunnii* and *E. pellita* had close low maximum MoE values of 13,768 and 14,328 MPa, respectively. For *E. pellita*, the regular occurrence of large knots, brittle heart, and decay could explain the low maximum modelled value. The maximum value for *E. nitens* was 15,698 MPa. The remaining three species (*E. cloeziana*, *C. citriodora*, and *E. globulus*), achieved analogous maximum fitted MoE values between 17,574 and 18,839 MPa.

Eucalyptus cloeziana had the highest rate at the inflexion point (248 MPa/mm), indicating the rate of MoE increase is the highest, or in other words, this species seemed to mature very quickly by comparison to the others. *Eucalyptus dunnii* also had a high rate at the inflexion point (223 MPa/mm); however, the low maximum MoE balanced out this benefit. *Corymbia citriodora* and *E. globulus* each exhibited a similar high rate at inflexion point (174 and 171 MPa/mm, respectively).

Despite a similar rate at inflexion, *C. citriodora* had a much lower inflexion point position than *E. globulus*. This indicates that higher MoE wood is produced much closer to the tree pith by comparison. However, *E. globulus* did produce a higher maximum MoE. *Eucalyptus pellita* displayed a lower rate of inflexion possibly impacted by the proportion of defects. *Eucalyptus nitens* had a very low rate at inflexion point (46 MPa/mm) and a high inflexion point position, meaning that the rate of MoE increase to maturity was very slow by comparison to the other species analysed. Consequently, the maximum MoE values were not reached until a relatively large diameter in the tree.

In terms of veneer production where processors peel billets to a fixed core diameter (*i.e.*, 45 mm for this trial), *E. nitens* would be expected to produce veneer with a large variation in MoE, with maximum MoE veneers only being able to be produced from a billet radius greater than 175 mm. By comparison, *C. citriodora* would be expected to produce veneer at a MoE level similar to *E. niten*'s maximum at a billet radius of approximately 60 mm, with higher MoE veneer being produced as the radius increases.

Figure 7 provides an example of the fitted sigmoid curve plotted with the actual MoE values across the radius for *E. globulus*. The wide data variability is obvious, especially as the radius is increased. This observation is further reflected in the coefficient of determination (R^2) values provided in Table 11 (0.31 for *E. globulus*). This wide variation however provides a true reflection of the qualities experienced during commercial processing, where samples contain defects and abnormalities as opposed to traditional 'clear wood' experimental samples. The latter would result in much less variability.

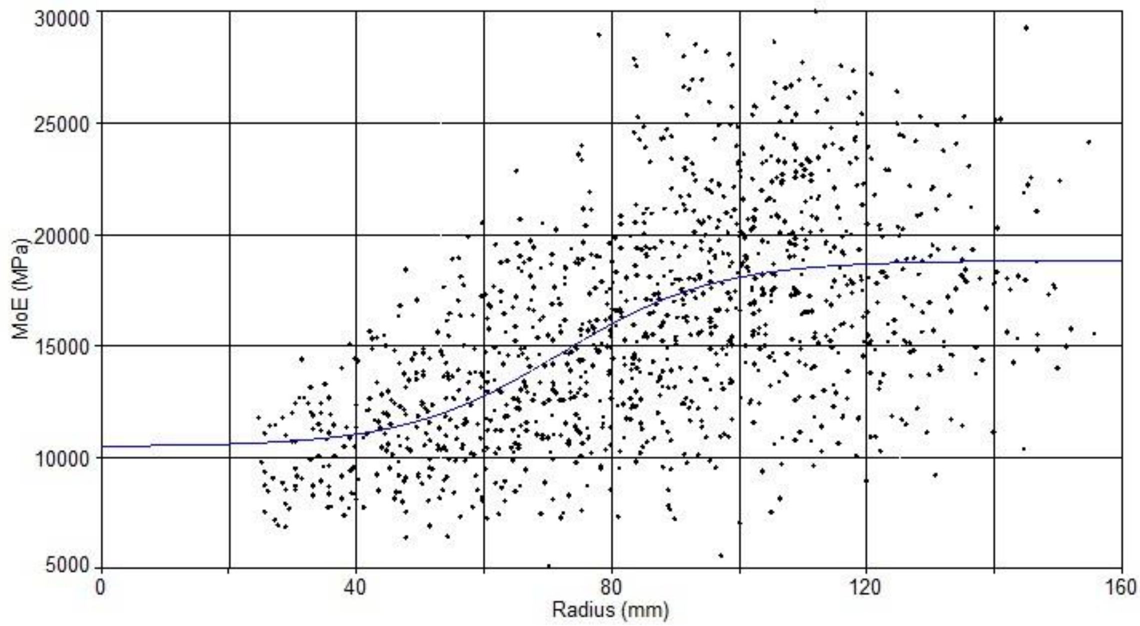

Fig. 7. *Eucalyptus globulus* modelled sigmoid curve for MoE across the radius and actual measured values

In contrast to the trends reported by Zobel and Sprague (1998) on some *Eucalyptus* species, a wide variation in properties (density, MoE, and specific MoE) measured from pith to bark was recorded for all trial species. The contrasted results could be explained by the growth characteristics of the trees sampled. Indeed, measurements performed, for example, on trees grown in natural forest display a very small area of juvenile wood in most cases. This is because of the slow growth typical of trees growing in such environments, which imposes high competition with other surrounding plants. This size effect (juvenile zone volume versus mature wood zone), combined with the sampling method generally applied (measurements on small prismatic beam), prevents the observation of large variations in wood properties (Bailleres *et al.* 2005).

This difference explains some of the negative experiences reported when young, fast-grown plantation resources have been processed into sawn timber sections, especially traditional larger dimensions. The large variation in properties that would result within one sawn board from the relatively young plantation resources could explain at least some of the instability (board distortion) commonly experienced during previous sawing trials (*i.e.*, Leggate *et al.* 2000; Washusen 2011). These problems are not experienced when sawing older native forest resources, even if the log diameters are similar. The explanation lies in the gradient of properties within the sawn dimension, which is much less steep from one board face to the other. This is a result of the slower growth of the native forest resource, which leaves the juvenile wood phase restricted to a much smaller radius (and potentially excluded while using many common sawing approaches).

The work performed to date, which show high recoveries of rotary veneer from young fast-grown plantation hardwood resources (McGavin *et al.* 2014a,b; 2015), potentially demonstrate a processing solution to better managing of the within log variability. Given the fact that rotary veneer is relatively thin and removed from the reducing log circumference, the end result is minimal variation in qualities from one side of the veneer to the other. The variability that is produced between veneer sheets can also be more easily managed to minimize final product variability and stability through the manufacture of engineered wood products (Cown 2005). This flexibility cannot be achieved with classical sawing techniques.

Similar to Table 11 and Figs. 6 and 7, Table 12 and Figs. 8 and 9 display the fitted parameters for density and MoE; however, the latter are presented along the veneer ribbon length. The analysis in this format has a greater relevance to the veneer processing industry, which is required to measure, sort, and manage the veneer qualities in the proportions generated as a result of billet diameter and the veneering process. Given the mathematical connection between the analyses methods, the trends and key observations are similar. *Eucalyptus dunnii*, *E. cloeziana*, and *C. citriodora* all transition from minimum to maximum MoE relatively quickly, meaning that the relative number of veneer sheets produced with low MoE is reduced. The impact of the low rate to maturity for *E. nitens* is more obvious when expressed along the veneer ribbon length. The result is a relatively large number of veneer sheets being produced with sub-optimum MoE. For example, veneer with MoE properties towards the maximum is not expected until nearly 40 m along the veneer ribbon length (measured from the billet core end of the ribbon). This could be problematic for processes if profitable products cannot be manufactured using this high proportion of low MoE veneers. Conversely, *C. citriodora* displayed attractive properties trajectories with a minimum MoE already in a higher range and a rapid increase to maximum values. *Eucalyptus cloeziana* had a lower MoE minimum, but a relatively fast transition towards maximum values, whereas *E. globulus*, despite having the highest maximum MoE, displayed a long transition phase.

An example of the fitted MoE sigmoid curve for *E. globulus* and the actual data is presented in Fig. 9. Similar to the discussion above, regarding Fig. 7, the large variability in measured values is obvious but is a true reflection of the challenges that commercial industry faces in managing variable veneer qualities.

Table 12. Fitted Parameters for Density and MoE along the Veneer Ribbon Length

	Parameters	*E. nitens*	*E. globulus*	*E. pellita*	*E. dunnii*	*C. citriodora*	*E. cloeziana*
Density (kg/m^3)	Minimum	562	587	723	511	727	578
	Maximum	632	780	754	639	832	821
	Inflexion position	7556	4758	2067	885	1543	1144
	Rate at inflexion	0.010	0.015	0.005	0.018	0.021	0.059
	R^2	0.11	0.32	0.03	0.13	0.19	0.28
MoE (MPa)	Minimum	12037	10304	11978	7659	13643	10200
	Maximum	15812	18732	14167	13470	18019	17502
	Inflexion position	1226	5434	1504	3084	2112	3014
	Rate at inflexion	0.13	0.96	0.29	11.67	0.64	2.00
	R^2	0.16	0.32	0.05	0.22	0.23	0.23

Many published observations support the idea that the radial evolution of intrinsic properties of wood related to cell wall formation, such as density and MoE, within a tree, are primarily influenced by cambial age rather than tree diameter (Zobel and van Buijtenen 1989; Bailleres *et al.* 2005; Kojima *et al.* 2009). A modelisation approach based on cambial age could provide useful tools to assess the potential of a given genetic resource in various growth and environmental conditions (Gion *et al.* 2011).

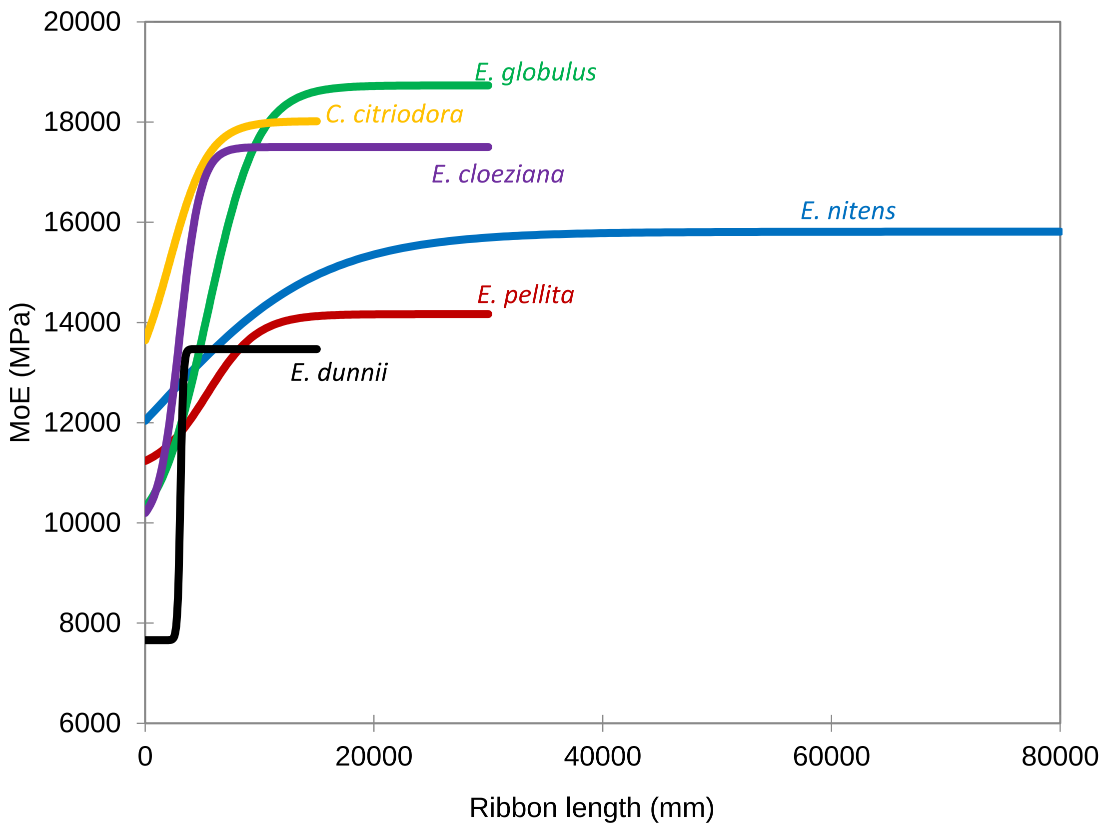

Fig. 8. Fitted MoE sigmoid curves along the veneer ribbon length for the six trialed species

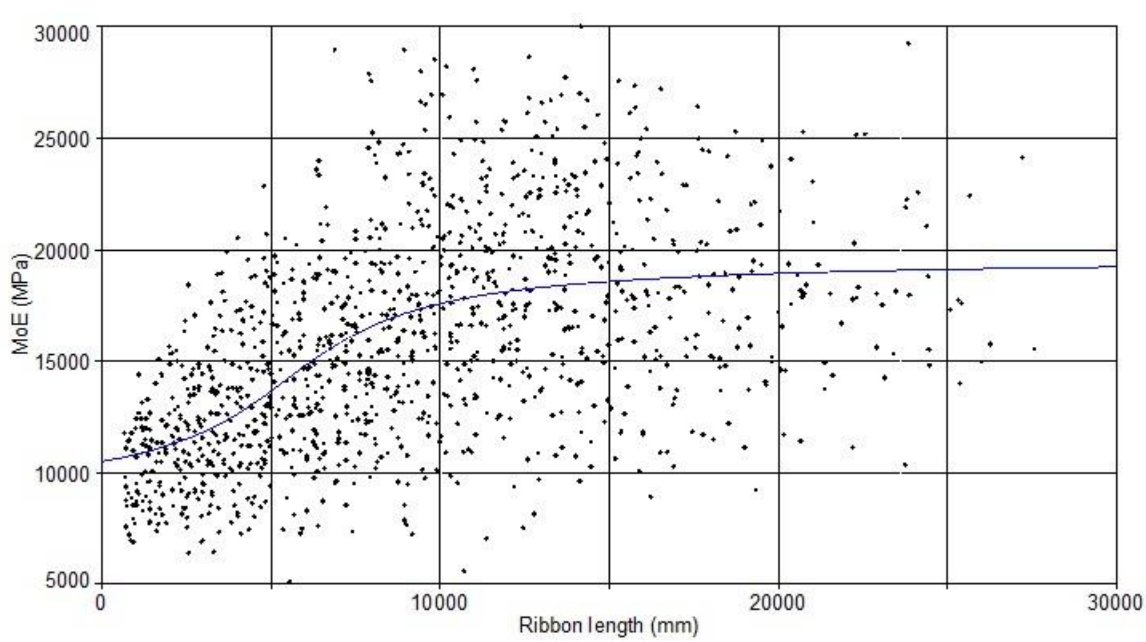

Fig. 9. *Eucalyptus globulus* fitted sigmoid curve for MoE along the veneer ribbon length and actual measured values

By adopting plantation management practices that emphasize rapid tree growth and targeting harvesting regimes driven primarily by tree diameters that match traditional processing requirements, the end result appears to be the ‘stretching’ of the zone of wood where the qualities are transitioning from juvenile to mature. Given the relatively young age of harvesting, compared to traditional native forest harvesting, plantation trees are being processed potentially before any substantial volumes of mature wood have developed (the upper plateauing of the sigmoid curve).

While further studies are required to explore these strategies, it would seem reasonable for tree breeding programs to consider the radial variation of key properties using the four sigmoid curve parameters as an important selection criterion, as demonstrated by Bailleres *et al.* (2005) and Gion *et al.* (2011). When targeting high performance structural products as an end-use, priority would be given to breeding lines that demonstrate early and quick maturation rates and high maximum values of key properties such as MoE. This would be expected to greatly improve the early production of larger volumes of more desirable, usable, and valuable wood for the processing industry. This would need to be balanced against other relevant selection factors and with economic considerations.

For the veneer processing sector, the utilization of the sigmoid model would be a useful approach to forecast and adjust the processing and target product strategies. For example, equipment investments and processing strategies that target improved recoveries through reduced peeler core size, may prove uneconomic if the forest resource has no capacity to yield veneer with suitable mechanical qualities in the relevant inner zone. Indeed, for forest resources that show late and slow maturation rates, it may prove more economic to produce larger peeler cores, even if the equipment has capacity to peel to a smaller core, and divert the larger cores which are unable to produce demanded properties to alternative processing and product streams.

In most of the modern veneer processing lines producing structural veneers, a grading process occurs, which often involves a series of segregation bins where commercial size veneers are grouped depending on mechanical properties and defect occurrence. The rules for this ranking process depends on an effective understanding of the resource qualities (including variability) and the type of product targeted (*i.e.*, structural performances required of the manufactured product). The sigmoid model approach can assist the processor understand the resource qualities and specifically the ratios in which these qualities are expected to be produced. The market can then use this to establish the most effective construction strategies that maximise the utilisation of the available qualities while meeting the product quality requirements.

CONCLUSIONS

1. This study demonstrated that there are large differences in density, MoE, and specific MoE between species and the ranking of species does not necessarily remain constant across these parameters. For density, there was a closer association between the more temperate species compared to the sub-tropical/tropical species. The between species variation was less for MoE compared to density and although the ranking order remained similar, the analysis did highlight that density is not always a good predictor of MoE, especially in commercial size samples which contain natural defects. Specific MoE analysis provided a substantial change in rank order with *E. nitens* outperforming

the other trial species. This could be an attractive attribute for this species where stiffness properties are required along with a critical threshold on product weight.

2. There was wide variation of properties within species, and the analysis methods adopted demonstrated and displayed the recovery of the qualities in a biological manner (pith to bark) and in a production format (veneer ribbon production). The analysis confirmed that the mean values do not necessarily provide the best method to compare between species or to evaluate a species. Indeed, the use of mean values for parameters such as density and MoE provide little value in determining optimal processing and manufacturing strategies, specific target end-products, or the potential output value of a resource. Instead, a clearer understanding of the variation, proportion of qualities, and the positioning within the billet or veneer ribbon is necessary to determine suitability and ultimately value.
3. Strategies based on simple mathematical modeling can help geneticists and processors to understand the quality of forest resources. The adoption of the sigmoid approach was demonstrated to effectively model the evolution of key wood properties. For tree breeding programs, selections targeting early and fast maturation rates along with favourable maximum values (*e.g.*, high maximum MoE) could lead to improved value recovery by the processor. The adoption of the sigmoid modeling for the processor would enable more efficient processing strategies to be adopted. It would also facilitate more accurate and efficient construction strategies for target final products.
4. The variation of properties that exists from potentially ‘stretching’ the juvenile zone over a greater proportion of the radius as a result of fast growth and relatively short rotation length provides a possible explanation or partial explanation for some the processing problems experienced with young fast-grown hardwood conversion, especially with sawn timber (*i.e.,* board instability). Veneer processing provides a much more attractive solution as the within sample variation is very much reduced. The opportunity to have greater control over the variability and gradients within the final product when using veneer would lead to a more stable and predictable product.

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